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PHYSICAL AND THERMAL DISTURBANCE AND PROTECTION OF PERMAFROST.(U)
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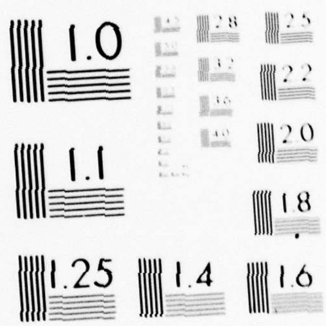

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PHYSICAL AND THERMAL DISTURBANCE AND PROTECTION OF PERMAFROST

J. Brown and N.A. Grave

UNITED STATES ARMY
CORPS OF ENGINEERS
COLD REGIONS RESEARCH AND ENGINEERING LABORATORY
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This report is based on a review paper presented at the Third International Conference on Permafrost held in July 1978 at Edmonton, Canada. It reviews the literature covering 1974-1978 and covers subjects related to natural and human induced disturbance of terrain underlain by permafrost. Subjects included regard investigations undertaken in conjunction with oil and gas pipelines, terrain mapping, methods for estimating terrain sensitivity, methods of protecting terrain, and the thermal effects of off road transportation, oil spills, fire, removal of the surface soil layers, snow conditions, mining and other construction practices. Methods of protecting and restoring permafrost in the USSR are presented in tabular form. An appendix summarizes results of modeling and microclimatic investigation, and the distribution and properties of subsea, land-based, and alpine permafrost.

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PREFACE

This report was prepared by Dr. Jerry Brown, Chief, Earth Sciences Branch, Research Division, U.S. Army Cold Regions Research and Engineering Laboratory; and Dr. N.A. Grave, Permafrost Institute, Siberian Branch, Academy of Sciences of the USSR, Yakutsk, USSR. Portions of the work were funded under DA Project 4A161102AT24, *Research in Snow, Ice and Frozen Ground*, Scientific Area B, *Cold Regions Environmental Interactions*, Work Unit 002, *Cold Regions Environmental Factors*. The paper was prepared as a contribution to the joint US-USSR Environmental Protection Agreement on the Protection of Northern Ecosystems, and was published as a review paper in Volume 2 of the Proceedings of the Third International Conference on Permafrost.

Mrs. Martha Andrews, Boulder, Colorado, assisted in the initial bibliographic compilation. Dr. V.N. Andreev, Biological Institute, Yakutsk, assisted in portions of the Soviet bibliographic compilation. Dr. Samuel Outcalt, University of Michigan, assisted in early phases of the modeling and thermal regime compilation as did Dr. A.V. Pavlov, Permafrost Institute, Yakutsk, on heat balance literature. Dr. Boris Vtiurin, Institute of Geography, Academy of Sciences of the USSR, Moscow, provided assistance on the Soviet mapping discussion. Mrs. Natalie Voshinin, U.S. Library of Congress Cold Regions Bibliographic Project, translated and cross-indexed the Soviet citations. Ms. Valentinia Paganuzzi, Canada, assisted in translation of the Soviet text. *Technical review of the report* was performed by Oscar J.Ferrians, Jr., of the U.S. Geological Survey, and Paul V. Sellmann of CRREL.

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PHYSICAL AND THERMAL DISTURBANCE AND PROTECTION OF PERMAFROST

J. Brown[1] and N.A. Grave[2]

[1]*U.S. Army Cold Regions Research and Engineering Laboratory*
Hanover, New Hampshire, USA
[2]*Permafrost Institute, Siberian Branch, Academy of Sciences of the USSR, Yakutsk, USSR*

INTRODUCTION

Since 1973 the trans-Alaska pipeline has been constructed, the limits of subsea permafrost in the Beaufort Sea have been investigated, the route has been selected for a large-diameter natural gas line running south from northern Alaska, construction of the Baikal-Amur Railroad (BAM) has progressed, and exploration for oil, gas, coal and other resources has continued throughout the mid- and high-latitude circumpolar regions. Those who have undertaken these massive construction and planning projects have considered many of the environmental impacts and hazards associated with permafrost and the problems involved in protecting and restoring the terrain (for instance Berger 1977a, b, Eddy 1974, Lysyk 1977, Mel'nikov 1976, National Energy Board 1977, Weller and Norton 1977).

Disturbance of the terrain, whether by natural or artificial causes, is bound to result in an acceleration of natural processes (Jahn 1976). Most factors that tend to disturb the natural environmental equilibrium are associated with human activity. But natural catastrophes occur as well: torrential rainfall, earthquakes, and fires. Terrain disturbance tends to increase the mean annual surface temperature. The active layer may become thicker and the thickness of the permafrost may decrease. The increase in thaw may be a few centimeters and be of little practical consequence, or we may observe gully formation, thermokarst development, landslides, and other forms of mass wasting. The magnitude of the disturbance depends mostly on the amount and type of buried ground ice, its proximity to the surface, the sediment type, and the time since disturbance.

This paper reviews the major findings of site and regional investigations dealing with human-induced and natural disturbances. Since the review paper by Bliss in this volume discusses the distribution and characteristics of arctic and subarctic vegetation, its relationship to permafrost, and natural and artificial revegetation, this review deals extensively with the physical and thermal aspects of terrain disturbance. A recently published paper by Webber and Ives (1978) discusses many aspects of tundra damage and recovery. It has not been possible to reference or discuss all available literature. In general, the references cited were published since 1974, although there are some earlier citations where considered pertinent.

Closely associated with terrain disturbance are subjects related to ground temperature regimes. Gold and Lachenbruch (1973) presented a major review on thermal conditions in the permafrost of North America. An update on ground temperature literature, mainly from North America, and associated microclimatic, energy exchange, and computer modeling studies are summarized in Appendix I. Microclimatic studies were an integral part of the investigations at the International Biological Program Tundra Biome sites at Barrow (Alaska), Devon Island (Canada), Niwot Ridge (Colorado) and several Scandinavian countries (Rosswall and Heal 1975). These studies, and the interest in modeling thermal processes associated with heated oil pipelines and proposed refrigerated gas pipelines and embankments, gave rise to many publications on computer modeling of soil thermal regimes and coupled heat and mass transfer processes (see, for instance, American Geophysical Union 1975, 1976). Specific aspects of the Soviet literature on ground thermal regime are presented in the text.

The first half of this report deals with literature from North American and other circumpolar regions, excluding the Soviet Union. The second half of the report contains the discussion of the Soviet literature.

REGIONAL STUDIES, MAPPING AND TERRAIN SENSITIVITY IN NORTH AMERICA

Environmental assessments and design considerations associated with large regional projects such as oil and gas pipelines have resulted in several major programs to study their potential impact upon permafrost. In Canada these efforts were accompanied by government-and industry-sponsored terrain and ecological investigations of the Mackenzie Valley and the Arctic Islands. The Mackenzie investigations began in the early 1970's and during the period of this survey a large number of government reports have been published in several series (reports of the Task Force on Northern Oil Development, Arctic Land Use Research (A.L.U.R.) and the *Environmental Studies* Series). In Alaska, preconstruction terrain mapping along the trans-Alaska pipeline was undertaken by industry (Kreig 1977). The Prudhoe Bay oil field provided an opportunity for developing a mapping scheme for evaluating various types of impacts (Everett et al. 1978).

Strang's (1973) study on the effects of disturbance at a wide range of sites in the Mackenzie Valley differentiated between non-damaging and detrimental changes. Change was deemed damaging if its effect extended beyond the area of initial impact. A change in floristic composition, a shallow depression, or a slight lowering of the permafrost table was rated not damaging. Accelerated bank erosion, siltation of a stream bed, and other outward spreading of a disturbance were considered harmful. Surface disturbance increased the average active layer thickness in the Mackenzie Plain by 23 cm, in the Peel Plateau by 21 cm, and in the Old Crow area by 10 cm. Causes of serious damage were the exposure of subsurface frozen soil on sloping ground (>5%), the intersection and diversion of drainage channels, travel on unfrozen wet ground, and the reuse of old roads or seismic lines. Several conclusions from these observations are: 1) sites underlain by ice-rich strata close to the surface are most vulnerable to disturbance, 2) any activity which modifies or destroys the organic layer causes some degree of damage, 3) sites undergoing recolonization are vulnerable to further disturbance, and 4) it is during the thaw season that the surface is most susceptible to disturbance.

A series of reports and maps describe the surficial deposits and landforms in the Mackenzie Transportation Corridor. They include rankings of the susceptibility of various terrain units to thermokarst, slope failure, gully erosion and other hazards (Hughes et al. 1973, Rampton 1974, Rutter et al. 1973, Zoltai and Pettapiece 1973). The distribution of terrain hazards related to thermokarst gullying and slope failure is controlled by the occurrence of high ice materials and massive ice beds. The hydraulic and thermal erosion resulting from the concentration of drainage along or adjacent to pipelines and roads constitutes a major hazard. The till plains afford the best potential routing and the glacio-lacustrine plains the most difficult, because of potential thermokarst conditions and highly unstable slopes. Slope failures are attributed to the thawing of frozen sediments, either due to thickening of the active layer or the undercutting of a slope. In the southern portion of the Mackenzie Corridor, areas of thick organic matter consisting of unfrozen fenland and ice-rich bogland pose the most significant problems in pipeline construction.

Kurfurst (1973) prepared preliminary terrain sensitivity maps of the Norman Wells area based on observations of terrain response to natural and human-induced disturbances. These included fire and removal of trees, surface vegetation and soils. Many of these activities were associated with exploration and drilling. He emphasized that the susceptibility of the terrain to disturbance is controlled by ground ice or moisture content, material type, slope, and relief. Bedrock, sands and gravels are least susceptible, till and organic sediments moderately susceptible, and clay and clayey silts most susceptible.

The results of many of these Mackenzie Valley investigations have been compiled and synthesized into two terrain sensitivity maps (1:1,000,000) in a report of the Environmental-Social Committee on Northern Pipelines (1975). The maps show surficial deposits, ecoregion, terrain sensitivity, disturbance level, and type of reaction. An ecoregion consists of land characterized by a distinctive regional climate. Terrain sensitivity was divided into seven classes based on the degree of reaction to terrain disturbance, and is dependent on ground ice, slope, material, and insulating cover. The mapped sensitivity ratings are indicative of maximum deterioration response. The presence or absence of permafrost and the type of ground are the two most important factors. Based on soil data from over 11,600 bore holes in the Mackenzie Valley, Heginbottom et al. (1978) concluded that the major factors controlling permafrost conditions were location (latitude) and soil texture.

An interdisciplinary mapping scheme for terrain characterization and evaluation was developed by Barnett et al. (1977) and illustrated for eastern Melville Island. The map scale is 1:250,000 and data are presented on a photomosaic base at three levels of detail: 1) landscape type (regional), 2) geobotanical facies (intermediate), and 3) terrain units (local). The subdivision into terrain units is based on criteria such as soil moisture, surface material, plant community, degree of dissection, and slope. The mapping scheme evaluates ground ice and engineering properties, trafficability, and sensitivity to overland travel and trenching. The approach provides a mechanism for combining natural subdivisions of the landscape (ecological, geological,

pedological) on a single map and considers surface materials as a key element of potential disturbance. Units are rated for sensitivity to several types of impacts.

Babb and Bliss (1974b) prepared a provisional map of the Queen Elizabeth Islands which emphasized the susceptibility of soils and vegetation to surface disturbance. Four broad categories were mapped: 1) Polar desert (31% of the land area), 2) Polar semi-desert (25%), 3) Diverse terrain (22%), and 4) Large meadows (<2%). Precautions or limitations for activities in each unit were presented. Although the Barnett et al. (1975, 1977) and Babb and Bliss (1974b) approaches differ considerably, both present useful information to planners when initial decisions are required for terrain utilization.

A more detailed approach to terrain sensitivity mapping has evolved at Prudhoe Bay which integrates soil and vegetation with respect to landform units at a scale of 1:6000 (Everett et al. 1978, Webber and Walker 1975). Ten landform units, six soil units and thirteen vegetation units are recognized. Soils and vegetation are displayed within the same landform boundaries and the result is referred to as a master map. Master maps provide the basis for generalization or for preparing very specialized interpretations. Depending upon the user's need, information may be extracted to form a derived map, for instance a map reflecting the thickness of the peat layer or the active layer for use in oil spill clean-ups. The most complex derived map is used to evaluate terrain sensitivity. A scheme for rating the impact of off-road, low pressure balloon-tired vehicles on vegetation was developed which described the type of disturbance and estimated the immediate and long-term impact (Walker et al. 1977). Oil spill sensitivity maps are being field-evaluated in conjunction with controlled and uncontrolled spills (Walker et al. 1978). Follow-up reports will evaluate the accuracy of the technique, and a terrain atlas of the Prudhoe Bay region is being prepared at CRREL by the same authors.

Terrain or landform analyses were an integral part of the design and construction of the trans-Alaska pipeline. Kreig (1977) and Kreig and Reger (1976) described the terrain unit map approach utilized in assessing the occurrence of thaw-unstable permafrost for purposes of locating material sources and evaluating slope stability conditions, and for other design requirements. The maps were prepared on a photomosaic base at a scale of 1:12,000 to show the landforms expected in a 3.5-kilometer-wide strip along the proposed oil pipeline route. Soil data from 3500 boreholes and numerous field observations were utilized. A 15-m depth profile was prepared of the geotechnical conditions anticipated along the pipeline centerline. An important contribution of the TAPS landform approach was the computerized data bank of soil and terrain conditions that was developed.

Several relationships governing the distribution of permafrost and the thickness of the active layer were evaluated by Dingman and Koutz (1974) in a small drainage area (1.8 km²) in interior Alaska. A solar radiation index, based on the concept of equivalent latitude and a function of slope and aspect, was shown to be closely related to vegetation and permafrost distribution. The boundary of permafrost in this region of discontinuous permafrost appears to coincide with an isopleth of 365 calories/cm²-day. The thickness of the active layer correlated significantly with the solar radiation index. Vegetation characteristics appeared least important in controlling active layer thickness. Also, in interior Alaska, Haugen and Brown (1978) indicated that the lower and cooler tundra-covered slope below timberline also favored the development of cold permafrost. This was associated with fine-grained soils and a shallow active layer (<60 cm as compared to >1 m on the upper slopes).

Several other permafrost-related mapping activities were also published. Sellmann et al. (1975), employing Landsat satellite imagery as an aid, developed a classification scheme for the thaw lakes of the Alaskan Arctic Coastal Plain that refined previous descriptions for these oriented lakes. It consists of six lake units and three non-lake units based on size, development of orientation of the elongated axis, lake density (percent water coverage), and controlling parameters such as regional or local relief and structural control. Methods were also discussed for estimating depth of water and potential maximum depth of thaw settlement and refinement of the transgressive history of the region. Using Landsat data, Tarnocai and Kristof (1976) developed a computer-aided classification and map of the terrestrial and aquatic environments on Richards Island, Canada. Spectral data were grouped into 14 terrestrial and 8 aquatic classes. Lathram (1974) was able to identify vehicular scars at Umiat, Alaska, using enlargements (1:80,000) of Landsat imagery. These tracks, which resulted from drilling activities in the period 1945 to 1952, were examined in the field in 1973. Well-developed beaded streams have formed on the ice-rich lowlands.

NATURAL PROCESSES

The development of natural thermokarst features has been summarized by Brown (1973) and Rampton (1973). Rampton concluded that thermokarst processes are still active in the Mackenzie–Beaufort region, but have slowed down, possibly reflecting a deteriorating climate in the area over the past 5000 years.

French (1974) described active thermokarst processes in eastern Banks Island. Broad and shallow ground ice slumps with a regional density of 0.5/km² are retreating at 6.0 to 8.0 m/yr. It is estimated that the slumps become stabilized within 30-50 summers. In the same area, thermal melting and erosion along ice wedges are resulting in the development of badland terrain (*baydzherakh*). Since the climate is probably not undergoing an unusual general warming, it was concluded that the active thermokarst is the result of local, nonclimatic factors.

Mackay (1978) measured radiant surface temperature data for thawing headwalls in ice-rich permafrost on

Gary Island. Headwall retreat had been active from 1963 to 1971 at a rate of 6 m/yr. All temperatures on the thawing headwall were above 0°C under bright sunshine. Surface temperatures increased rapidly as muddy water flowed downslope, rising 5° to 10°C in less than one minute.

Thie (1974), using aerial photography acquired over a 20-year period, measured the degradation of permafrost in the southern part of the discontinuous permafrost zone in Manitoba. The observations were based on peripheral and central collapse in palsas and peat plateaus. Retreat due to edge collapse was as much as 20 m. Up to 60% of the land portion of this area once contained permafrost, now only 15% does. This degradation apparently has been active over the past several centuries.

Priesnitz and Schunke (1978) reported on the permafrost of central Iceland, where both degradation and aggradation processes are or have been active. The permafrost is up to 6 m thick. Thermokarst depressions, valleys and mounds are described as degradation forms. Over 1200 palsas have been mapped and are considered to be indicators of aggrading permafrost.

Ugolini (1975) described an unusual form of thermokarst along the Noatak River Delta in Alaska. He suggested that upon melting, ice-rafted sediments deposited a layer of mud on the permafrost terrain, which in turn resulted in increased thawing, subsidence and subsequent pond formation.

The quickest way to measure thaw is to force a small-diameter rod into the soil to the point of refusal. However, these determinations of thaw depth are subject to error. Mackay (1977a), using a temperature probe and metal probes of varying diameters, evaluated the results obtained this way under different soil and ice conditions on the Tuktoyaktuk Peninsula. Firm resistance to probing corresponded to the 0°C isotherm in icy, organic soils, ice-bonded coarse-grained soils, and ice-lensed fine-grained soils. But in fine-grained soils free of ice lenses, probes could usually be pushed beyond the 0°C frost table. The large unfrozen pore water content of silty clay and clay soils can lead to overestimates of several decimeters in the depth of the frost table. In such soils, larger diameter probes may give a better physical estimate of the 0°C isotherm.

The depth of thaw along the coast of northern Alaska has been investigated at several sites, e.g. Peard Bay (Harper et al. 1978, Owens and Harper 1977) and Pingok Island (Fisher 1977). Thaw measurements along four profiles across a 55-m-wide barrier pit and a beach backed by a tundra bluff revealed that the spit experienced the greater thaw. In the gravel of the spit the rate of thaw increased during late summer, with 0.6 to 0.7 cm/day being measured as opposed to the more usual rates of 0.2 to 0.4 cm/day in soils. This greater rate was attributed to the nearshore water with its higher heat capacity and salinity. Total mean seasonal thaw ranged from 93 to 131 cm across the four profiles.

In a related detailed investigation of thaw depths on Pingok Island in the Beaufort Sea off Alaska, the normal exponential seasonal decrease in thaw was noted (Fisher 1977). Here the base of the active layer generally conformed to surface polygon configuration. An inversion of surface topography developed beneath hummocks and over the ice wedges that were close to the surface. Slope exposure was found to affect the thickness of the active layer significantly, whereas moisture content and sediment size had only minor effects. The southwest slopes had thicker active layers than the southeast slopes, which were about the same as the north-facing slopes. The vegetation cover was the dominant factor in influencing the thickness of the active layer; unvegetated sites had over 100 cm of thaw, while vegetated areas had 30-60 cm.

Brown et al. (1975) presented thaw data for major soil conditions at Prudhoe Bay: <30 cm for dry organic soils, 40 cm for silty dry meadow tundra, 60 cm for sandy dry meadow tundra, and >90 cm for sandy upland tundra. From the same area, Walker and Webber (1978) reported thaw increases as a function of distance from the cold bay: 22 cm near the bay and 33 cm inland. A strong summer air temperature gradient exists from the shore of the Arctic Ocean inland several tens of kilometers (pers. comm., R.K. Haugen, CRREL).

Peterson and Billings (1978) investigated the interaction of vegetation patterns and geomorphic processes along sandy bluffs in northern Alaska. Maximum depth of thaw occurs near the edges of the bluffs and exceeds 100 cm. Within 50 m of the edge, values decrease to less than 40 cm. The sand deposits were observed to be stabilized by the presence of the permafrost table, which rises as vegetational cover increases.

Nicholson and Lewis (1976) investigated the deeper thaw (10-12 m) under drainage lines in Schefferville, Quebec. Normal active layer thicknesses in the region range from 2.4 m under continuous vegetation to 3.6 m under bare ground. Nicholson (1978b) indicated that permafrost is actively developing in mine waste dumps (8-10 m in 10 years) at Schefferville and that areas deforested by fire and having shallow snow cover may develop 10-20 m of permafrost over a 25-30 year period of revegetation.

Hannell (1973) correlated depth of thaw with the 1-cm-deep daily temperature. The emphasis was on slopes of approximately 30° on the southwest coast of Devon Island. Contrary to accepted principle, active layers on north-facing slopes were consistently 5-10 cm thicker (20-40 cm on the south-facing slopes and 25-45 cm on the north-facing slopes). Active layer thickness increased as the slope of the surface declined, with 52-cm depth found on an 18° slope as opposed to 40-47 cm on a 29° slope.

Ponds and lakes on the Colville Delta, northern Alaska, are dynamic features of that landscape. Walker and Harris (1976) described perched intradune ponds with depths of up to 1.3 m. The restricted thawing of the active layer insures maintenance of the pond level above the regional "water table" throughout the summer. Total thaw beneath the pond is only about 60% of that beneath the exposed sand dunes. Maximum depth

of thaw in the ponds is about 110 cm. These ponds are relatively short-lived as either filling by the blowing sand or drainage by headward erosion leads to their extinction. Walker (1978) describes the process of lake tapping. As the lake enlarges and the river erodes lakeward, thawing of ice wedges creates channels through which the river can overflow. Further erosion results in partial or complete draining of the lake. Other papers on the Alaskan lakes discussed the role of lineament control in lake orientation (Short and Wright 1974) and compared the origin of the Carolina Bays with the Alaskan oriented lakes (Kaczorowski 1977).

Erosion of permafrost along river banks and shorelines is a natural form of terrain disturbance. Cooper and Hollingshead (1973) reported on several cases of bank erosion in the Yukon Territory and emphasized that the active layer annually provides an easily erodable and unstable slope material. Newbury et al. (1978) concluded that shoreline erosion in reservoirs on permafrost occurs through a combination of thermal and mechanical processes that cause a deep niche to form immediately below the waterline, which then leads to slumping. Ritchie and Walker (1974) identified nine forms of river banks along the Colville River, four of which were erosional, four depositional, and one neutral. Thermal erosion and thawing result in the development of niches along the bases of the banks. Bank collapse and block sloping are common. Harper (1978) indicated that the average rate of coastline retreat between Peard Bay and Barrow, Alaska, is 0.31 m/yr. Code (1973) mapped the stability of river banks along the Mackenzie River and its tributaries.

In several papers, McRoberts and Morgenstern (1974a, b) emphasized the important role thawing plays in a wide range of landslide types associated with permafrost. The most common landslides of thawed materials are flow-dominated and are subdivided into solifluction, skin flows and bimodal flows. Slope failures on frozen soils were classified and analyzed as block and multiple retrogressive.

Zoltai et al. (1978) sampled a large number of earth hummocks from the Canadian Arctic and reported radiocarbon dates from the buried peats and organics. Most of the samples were 3000 to 4000 years old. These dates correspond to a climatic change toward colder and moister conditions about 4500 years ago, conditions which presumably would favor an intensification of frost action and peat burial.

HUMAN-INDUCED DISTURBANCES

Human activities which initiate disturbance can be divided into 1) point activities and 2) extensive activities (Barnett et al. 1975). Point activities include airstrips, staging areas, drill sites and town sites. Extensive activities include survey lines, pipelines, winter roads and all-year roads. Disturbance can be quantitatively evaluated in several terms of reference or combinations: 1) visual impact, 2) physical terrain modifications such as an increase in active layer thickness, settlement, and compaction, and 3) ecological impact and ability to recover. How (1974), in an assessment of the effects of the proposed gas pipeline construction on the terrain found in the Mackenzie Valley, summarized the major causes of human-induced impacts and the mechanism and consequences of each (Table 1). Brown et al. (1978) discussed the following causes of tundra disturbance, many of which are found in the western U.S.: grazing, recreation, mining, roads, pipelines, powerlines and reservoirs.

Heginbottom (1973, 1974-75) discussed three main causes of disturbance as being related to human settlements, forest fires, and oil and gas exploration activities. Where bulldozers cleared trails in summer by simply pushing over trees and leaving the forest mat in place, thaw conditions under it and the adjacent undisturbed sites remained essentially the same. When the vegetation mat was pushed aside, deep thaw and slumping occurred. Surface disturbance results in compaction of the surface soil, which in turn alters the soil thermal properties, while removal of the surface alters the albedo. The downward flux of heat in summer increases following physical disturbance, causing warming of the permafrost and deeper thawing. Subsidence occurs as excess ice melts and water drains. On sloping terrain, slope failures, mass movement and landslides occur. Coarse-grained soils are more resistant to these forms of disturbance.

The following sections discuss the response of permafrost terrain to a variety of human activities. Fire disturbance, although generally considered a natural phenomenon, is included in this discussion primarily because it is frequently compared with other forms of human-induced disturbances.

Off-road transportation

In the absence of established roads, surface transportation is now restricted to environmentally nondestructive modes. In winter this is accomplished using over-snow tracked vehicles or, on snow and ice roads, by more conventional wheeled vehicles. In summer, experimental machines such as low pressure balloon-tired vehicles (Rolligons) and air cushion vehicles (ACVs) are being used. Rickard and Brown (1974) reviewed much of the available literature on summer off-road vehicular impact. The U.S. Bureau of Land Management sponsors and publishes surface protection seminars (Evans 1976, 1977) at which numerous individual reports are presented on problems and their solutions associated with off-road impact, transportation, and protection of the terrain. A number of experimental investigations have been undertaken to observe the performance and potential impact of both summer and winter vehicles. The physical damage to the terrain that results from off-road vehicular movement is potentially more serious on the wetter, ice-rich permafrost terrain than on drier terrain, where visual impact may be the extent of the damage.

Table 1. Summary of terrain impacts in North America (after How, 1974).

Cause	Mechanism	Possible consequence	Severity of problem: South of latitude 65°	Severity of problem: North of latitude 65°
Clearing	Removes trees and shrubs, compresses peat slightly, increases depth of thaw	Thermokarst subsidence, ponding, slumping	Minor subsidence, local slumping	Minor subsidence
Grading (cut)	Exposes mineral soil to increased heat input, increases rate and depth of thaw	Subsidence, slumping, gullying	Gullying by mechanical erosion, minor subsidence	Subsidence, slumping, gullying (active for more than 5 years)
Traffic on winter roads	Reduces vegetation cover, compresses peat layer, increases depth of thaw	Subsidence, ponding, slumping	Minor subsidence, local ponding and slumping	Short-term effects: minor subsidence and ponding. Long term effects uncertain
Traffic in summer	Compresses, damages, and strips off peat layer, increases rate and depth of thaw	Rutting, thermokarst subsidence, ponding, slumping	Minor subsidence mechanical erosion of slopes to form gullies	Short-term effects of multiple passes of vehicles: rutting and subsidence. Long-term effects: subsidence, gullying and slumping
Roads and airstrips	Keeps surface generally clear of snow, allowing greater frost penetration	Ground icings, choking and diverting of drainage during breakup	Icing problem can be reduced or solved with use of proper control measures	

Winter roads and trails

This section reviews studies concerned with the effects of winter road construction on the terrain and does not discuss methods of construction or the properties of ice and snow roads.

Adam and Hernandez (1977) described the Norman Wells forested test loop, which was built in March 1973 and was subjected to 36,000 passes by several types of tracked vehicles. For comparison, thaw depths were also obtained from adjacent plots that were cleared by hand and by machine, and areas that were slash-burned. A nearby seismic line, cleared in October 1971, was also used for comparison. Measurement of the active layer thickness the first summer (1973) showed that clearing of the land by hand and by machine had increased thaw to 44 and 59 cm, respectively, as compared to 36 cm in the undisturbed forested site. The ice and ice-capped portions of the snow road had 59 and 63 cm of thaw, respectively. The seismic trail, which had had several summers of increased thaw and additional foot traffic during access to the test site had a thaw depth of 82 cm. Subsidence of the surface of the seismic trail was about 30 cm. This area, however, is not underlain by excessively ice-rich sediment. The second year (1974) of thaw showed increases of 10 cm in the control area, 14 cm in the ice road, and 13 cm in the ice-capped snow road. The depth of thaw in the seismic trail in the fourth year was essentially the same as in prior years, suggesting a thaw equilibrium or recovery on that site. The conclusion of the study was that snow roads could be constructed in a way that would protect the permafrost. However, additional precautions would be needed on ice-rich subsoils.

Haag and Bliss (1974a), in their energy budget investigations of upland tundra at Tuktoyaktuk, reported on a winter road from which all the vegetation and most of the surface peat had been removed or compacted. Thaw on the winter road was 55 cm compared to 33 cm for the undisturbed surface. The surface subsided approximately 15 cm.

Younkin and Hettinger (1978) presented results from the Inuvik processed snow road which was built in winter 1973-74. This road received 1000 vehicle passes, mainly with a tandem tractor and trailer. Before the test the active layer thickness averaged 42 cm. The mean active layer thickness in the road and the cleared area decreased 2 cm and 1 cm respectively in 1974 and increased 4 cm in 1975 where it remained in 1976. No significant change in elevation was noted. These results substantiate other similar findings that the peat layer has a greater influence on depth of thaw than either albedo or the effect of living vegetation (Haag and Bliss 1974a).

Kerfoot (1974) described topographic disturbance resulting from cross-tundra movement of tracked vehicles on the Tuktoyaktuk Peninsula and winter road in the vicinity of Sitidgi Creek. For topographic features which resulted from the 1965 blading of ice-rich tundra, 63.5 cm (41%) was the result of thermokarst subsidence, and the remainder of the relief was due to removal and redistribution of debris. Subsidence or decrease in

ground surface elevation along a winter snow road (1964-1965) was estimated to be 84 cm, while the actual observed was 64. By summer 1966 field evidence indicated that a new quasi-equilibrium condition in the thickness of the active layer had been attained.

Racine (1977) reported on surface disturbance (and subsequent recovery) resulting from a 1974 winter oil exploration and drilling operation on the northern part of the Seward Peninsula. The snow road caused less damage to the vegetation than did the activities at the drill storage pads, which were located in stabilized sand dunes and beach ridges.

Summer off-road traffic

Rickard and Brown (1974) summarized the results of off-road vehicle experiments initiated in 1968-71 at Barrow and Prudhoe Bay, and in the Mackenzie Delta and the Arctic Islands.

Hernandez (1973) compared the disturbance caused by winter roads and summer seismic lines in the Mackenzie Delta and the Tuktoyaktuk region. In the forested and shrub communities north of Inuvik, silty soils thawed 60-70% deeper in the disturbed areas than in the controls (16-22 cm in the control and 27-40 cm in the disturbed areas over three summers of observations). In a tall shrub community near Tununuk Point, thaw doubled in the disturbed areas (29 cm in the control and 60 cm in the center of a seismic trail in early July). For tundra communities near Atkinson Point, the depth of thaw under trails increased only slightly, although the thaw under an old airstrip on which 1-2 m of sand had been placed in the mid-1950's more than doubled. In a tussock tundra community near Reindeer Station, a trail made by a vehicle train resulted in erosion, slumps and more than doubling of the thaw depth by early July. In the Tuktoyaktuk region winter roads used for several winters produced thaw 27 to 44% deeper under the center of the road than in the adjacent undisturbed areas. Where the surface peat had been worn down over ice wedges, thermokarst and gullying occurred. A comparison was also made of summer and winter seismic lines through similar plant communities. Thaw averaged 58 cm under the summer seismic line and 29 to 38 cm under the three winter lines (controls ranged between 19 and 30 cm in mid-July). Subsidence of the bladed summer trail was estimated at 25-30 cm and thermokarst ponds formed where ice masses were exposed. Winter trails did not result in massive thermokarst subsidence since only a small amount of soil was exposed. For this region, thaw generally increased 80 to 100% where mineral soil was exposed, 30 to 50% if the peat remained intact, and 10% if the plant cover was little altered.

Addison (1975), Babb (1977), Babb and Bliss (1974a) and Barrett (1975) reported on a series of controlled surface manipulations and observations of disturbances at a number of extensive sites in the Canadian Arctic Islands. Multiple passes (10, 40 and 60) of a vehicle with rubber tracks (Ranger) on a meadow site resulted in no significant thaw differences during the first season. A simulated blading experiment in which the top 3 cm of peat was removed resulted in only a small increase in thaw (approximately 5 cm). It was concluded that erosion and thermokarst resulting from increased soil heat flux in disturbed surfaces are relatively minor problems in the High Arctic.

Abele (1976) and Abele and Brown (1976) presented long-term results of multiple-pass testing of air cushion and tracked vehicles (Weasel) and low pressure tired vehicles at Barrow. For the worst case, thaw continued to increase for several years following 50 passes of the tracked vehicle and the air cushion vehicle. The maximum increase in thaw was 11 cm for the Weasel and 5 cm for the air cushion vehicle. The area contained relatively low amounts of ground ice. Visual deterioration began to improve during the second growing season following the tests, and in areas that received 25 and 50 passes signs left by the vehicles were barely perceptible after 4 years. The visual impact is more severe in wet tundra than in dry, polygonal tundra.

In a related study Abele et al. (1978) initiated another multiple vehicle test at Lonely, Alaska, the current base camp for oil and gas exploration in the National Petroleum Reserve, Alaska. This test involved 1, 5 and 25 passes of several types of Rolligons and a Nodwell tracked vehicle. After two seasons, differences in thaw depth were negligible in all test lanes. In a related test at Prudhoe Bay single and multiple passes were made by a Rolligon across a range of vegetation and soil types early in the summer (Everett et al. 1978, Walker et al. 1977). The tundra was extremely wet and thaw still shallow (12-28 cm). Thaw observations were made and impact ratings assigned at 32 stations. By mid-July of the second summer (1977) following the test, differences in thaw between the track and the control surface were either negligible or the thaw averaged 3 cm deeper in the trail (pers. comm., Walker). In these observations no damage had spread from the Rolligon test area to the adjacent tundra. This is in agreement with the Muskeg Institute's observations (Radforth and Burwash 1977) that rarely did deterioration of the terrain go beyond the immediate tracks.

Radforth (1973) reports on the long-term effects at tracked vehicle test sites at Tuktoyaktuk and Tununuk, N.W.T., and Shingle Point, Yukon Territory. Thermokarst development was related to the level of initial disturbance, although all terrain types tested stabilized within two years. It was concluded that vehicle traffic in excess of 40 passes should be avoided to minimize surface disturbance.

Gersper and Challinor (1975) reported on physical changes in an old Weasel trail at Barrow. Soil bulk densities and temperatures were higher, thaw was deeper, and moisture was lower under the track than in the adjacent undisturbed tundra. Thaw in the control area was 30 cm while at several positions in the track it averaged 42 cm. The wetter sites had greater thaw. Where the trails intercepted ice wedges close to the surface, shallow thermokarst pits had formed.

Sparrow et al. (1978) studied five trails on alpine soils and vegetation in central Alaska and found that in mid-July thaw depths were more than 1 m under the trails and ranged between 40 and 70 cm in the undisturbed tundra. The wetter areas and side slopes, which are highly erodable, showed the greatest visual impact.

Rickard and Slaughter (1973) monitored permafrost degradation and erosion on a tractor-cleared trail and on a hand-cleared access trail near Fairbanks. Under the severely eroded tractor-cleared trail depth of thaw had increased to between 132 and 189 cm while thaw in the adjacent undisturbed area was 36-48 cm. On the hand-cleared trail thaw had increased from control values of 54-59 cm to 127-182 cm. The hand-cleared trails had been used for four summers while the bulldozed trail was used once.

Linear transportation systems and other activities

Roads, railroads and pipelines have considerable potential for modifying the highly variable permafrost terrain they traverse. The response of the permafrost environment varies, depending on physical and thermal conditions. Proper route selection, drilling programs, and design can eliminate much potential terrain disturbance. Recent experience along the Livengood to Prudhoe Bay haul road, the Dempster, Alaskan and Mackenzie highways and the old Canol road (Fradkin 1977) has produced numerous documented examples of terrain disturbance due to road construction. Major causes of disturbance due to linear placement of gravel for road beds and pipelines are:

1. Concentration of sheet flow through drainage structures and subsequent downslope thermal and hydraulic erosion in ice-rich permafrost.

2. Cuts through massive ground ice and subsequent accelerated melting and thawing, with production of sediment and potential for rapid headward erosion.

Secondary effects are:

1. Local surface impoundments where ponding may accelerate thaw adjacent to and beneath the roadbed and result in local impact on vegetation.

2. Increased snow accumulation due to drifting and potential warming of the permafrost.

Isaacs (1974) investigated the thermal modifications caused by the Canol road, which was built in 1943 between Norman Wells and Whitehorse. As a result of surface warming the underlying permafrost has warmed considerably. Calculated thaw depths, assuming conduction processes only, underestimated the depth of thaw as observed in drilling. In one area thaw was calculated to be 15 m but no permafrost was found in the 25-m-deep hole.

Pufahl et al. (1974) reported on a field reconnaissance of road cuts in northwestern Canada and parts of Alaska. It was noted that the greatest risk of initiating unstable slope conditions arises in areas of glacio-lacustrine silts and clays which contain large amounts of ground ice. They concluded that instability of natural slopes is the best indicator of potential instability of cut slopes. Their observations indicated that cut slopes need not be a serious impediment to routing transportation arteries across permafrost.

Berg and Smith (1976) reported on the slope stabilization of the TAPS road over a 6-year period. They concluded that natural processes of slope stabilization in ice-rich cuts can be enhanced if: 1) lateral drainage ditches are wide enough to allow deposition and removal of material, 2) backslope cuts are cut nearly vertically and 3) the tops of cuts are hand cleared to a width equal to one and one-half times the height of the cut.

Berg et al. (1978) reported on the initial thaw performance of the Yukon River-Prudhoe Bay haul road and indicated that concentration of sheet flow through culverts on the ice-rich slopes is a serious design and terrain problem.

McPhail et al. (1976) also reported on stabilization of cuts along the haul road. The Happy Valley road cut is cited as an example in which thawing of gravelly silt caused considerable maintenance problems. Special restoration techniques were required. The adjacent cut with massive ground ice healed naturally.

Huculak et al. (1978), reporting on the Dempster Highway construction, said that the prime design concern was to preserve the permafrost to a tolerable degree of grade distortion.

Considerable attention has been devoted to erosion control and related revegetation during and after the construction of the trans-Alaska pipeline. In an initial report Johnson et al. (1977) documented the summer 1975 performance of initial revegetation and erosion control techniques and presented illustrated examples of slides, slumps, thermokarst, and thermal erosion along the route. The natural folding over of the organic mat on road cuts was successful in stabilizing cuts.

The Arctic is not the only tundra region where pipeline construction activities may cause temporary disturbance (Brown et al. 1978). As an example, Marr et al. (1974) described placement of a gas line which crossed the alpine tundra of Colorado. Erosion potential during spring runoff when the ground is frozen was considered high and the routing was selected to intercept a minimum of existing drainages. Construction was delayed until the turf vegetation was dry to avoid damage, and techniques for placing the turf back over the trench were experimented with for purposes of restoration.

The experience gained in road and pipeline construction across permafrost and muskeg terrain has led to revised environmental design and construction guidelines for roadways on permafrost (Murfitt et al. 1976, Lotspeich and Helmers 1974, Curran and Etter 1976). Some major points are listed: 1) The vegetation mat should remain in place to minimize thermal erosion and thermokarst. 2) Grading, particularly in ice-rich soils, should be avoided and fills used as an alternative. 3) Natural drainage should be maintained and additional drainage for runoff considered. 4) Design should incorporate tolerable amounts of settlement. 5) Surface and groundwater seepage areas and frost-susceptible

materials should be avoided where possible. 6) Drainage structures should be designed to minimize water-related erosion. 7) Embankment surface drainage must be accounted for in the design and maintained during construction.

French (1975) described a case history of human-induced thermokarst due to construction of a gravel airstrip at Sachs Harbour on Banks Island between 1959 and 1962. Hummocky-type terrain with maximum relief of 100-150 cm has been created by progressive subsidence and thermokarst modification. Thaw depths were 10-20 cm greater under the disturbed sites. After 10-12 years, the thermokarst process continued but at a lower rate, although thermokarst forms were well-developed several years after the initial disturbance.

Price et al. (1974) described wet spots found on surfaces scraped for runways and other access sites on the Queen Elizabeth Islands. The spots are associated with non-sorted polygons. As the underlying ice-rich zones around the margins of the polygons thaw, due to the disturbance, moisture is drawn to the surface. Over the course of several summers the excess ice is removed and the spots dry out.

Walmsley and Lavkulich (1975) examined the effects of organic matter removal on the active layer over a period of one year in an area 80 km east of Fort Simpson. In a peat plateau, thaw in a trench increased from 30 cm in July 1971 to 90 cm in July 1972. The disturbance influence was still measurable 2 m from the trench, with thaw 40-60 cm deep. In a polygonal bog, lateral thaw along an ice wedge increased the disturbed area to more than 4 m.

In a study of a 1949 exploratory drill site in northern Alaska Lawson et al. (1978) observed thaw as a function of intensity of disturbance; mean thaw depth was 53 cm on intensely disturbed sites as compared to 32 cm on the least disturbed.

Oil spills

Research on experimental terrestrial crude oil spills started in 1970 at Barrow (Deneke et al. 1975) and at three locations in the Mackenzie Delta (Wein and Bliss 1973b). Additional experimental spills were conducted in Fairbanks (Jenkins et al. 1978), Barrow (Everett 1978), Prudhoe Bay (McKendrick and Mitchell 1978, Walker et al. 1978) and in Canada (Hutchinson et al. 1976, Mackay et al. 1975a, b). Although the intent of many of these spills was to evaluate the fate of the crude oil and its effect on biological components, soil temperature and thaw depth were also measured to evaluate the potential effects of the movement of the oil on the permafrost table.

Hutchinson and Freedman (1975) and Freedman and Hutchinson (1976) reported insignificant differences in the active layer under spills at Norman Wells and Tuktoyaktuk compared to their controls. During a three-year period of measurements the only exception was a wet meadow spill at Tuktoyaktuk which had much deeper thaw than the control in both 1974 and 1975. Summer spills are more harmful to vegetation than winter spills. Oiled plots tend to have higher surface temperatures due to increased radiation absorption on the surfaces darkened by the oil (Haag and Bliss 1974a). However, these higher surface temperatures do not generally lead to increased depth of the active layer on the oiled sites. Extra energy absorbed apparently is lost as latent heat of evaporation and the resulting drier surface forms an effective thermal barrier.

Dickman and Lunardini (1973) observed thaw depths one year after applying crude oil to hummocky terrain at Inuvik. Thaw increased between hummocks and decreased under the hummocks. These results indicated the rather complex behavior of oil in the active layer.

At Barrow, Everett (1978) observed a marked increase in thaw depth during the first two summers after application of crude oil (1975 and 1976). The effect diminished in 1977 and it was suggested that the effect is probably of short duration, on the order of five years or less.

Hydrocarbons persist in the active layer for more than 30 years as observed on 1948 and 1949 drill sites in northern Alaska (Lawson et al. 1978) and along the Haines-Fairbanks pipeline for a period exceeding 20 years (Deneke et al. 1975). In the latter, the permafrost table receded where vegetation had been killed, but where a thick moss layer existed changes in active layer thickness as well as erosion were minor or not detectable. At the Fairbanks 1976 winter and summer spills of hot crude oil there was little movement of oil downslope after the first season (Jenkins et al. 1978). An increased rate of thaw in July and August was noted for the summer spill as compared to the winter spill. Natural oil seeps at Cape Simpson indicated thaw in the seeps was 40-50 cm deep and diminished abruptly to 25 cm adjacent to the seep (Deneke et al. 1975). Temperatures were 3 to 5°C warmer in the seeps during the day at 10-cm depth and 1-2°C warmer at night compared with the adjacent tundra.

Containment of spills by damming in permafrost and damage by vehicles could result in increased disturbance. Greene et al. (1975) proposed a portable corrugated metal sheeting which could be installed by hand to contain the oil. Other techniques involve cutting narrow trenches (30 cm wide) which intercept the oil, which can then be pumped. It is suggested these techniques might be less degrading to the environment than burning, although McKendrick and Mitchell (1978) report no significant thermal or thaw changes resulting from burning spilled oil in Alaska.

Mackay et al. (1975a) indicated that some effects of oil on the thermal regime could be: 1) an albedo increase that would increase the mean surface temperature by 10%, 2) an increase of 10-20% in thermal conductivity if the oil was physically trapped in voids contained in mosses, 3) an increase in thaw if oil occupies the voids instead of ice since the latent heat to melt ice would not be required, and 4) an increase in the soil temperature due to reduced evaporation caused by the oil film.

Raisbeck and Mohtadi (1974) developed a simple model to predict the movement of oil on permeable and impermeable surfaces. Oil is likely to spread above the

groundwater table. The question was raised whether the oil's ability to absorb extra energy would in fact result in greater thaw. Oil-inundated soils have a lower thermal conductivity, which reduces heat transfer. This may be the reason for the lack of strong evidence that oil in soil increases thaw.

Fire

Fire in the tundra and northern coniferous forest (taiga) is a common natural process frequently initiated by lightning storms. Viereck (1973, 1975) states that "fire is undoubtedly one of the most important environmental factors affecting taiga ecosystems." In Alaska, of the 400,000 hectares burned between 1940 and 1969, nearly half was treeless bogs, fens and tundra. Hernandez (1974) reported that one million hectares burned in the period 1962-71 in the District of Mackenzie, N.W.T., and the Yukon Territory north of 67° latitude. Wein (1976) reported on over 50 tundra fires, mostly in western North America. Shilts (1975) added to the list of tundra fires for the eastern Arctic, aided by the use of satellite imagery. Generally tundra fires are smaller than forest fires because of the lack of combustible materials.

Following fire, the active layer undergoes some modification and usually increases in thickness. Secondary effects of fire on the permafrost terrain result from erosion and gully formation, particularly where fire lines have been bladed or cleared with bulldozers (Evans 1976).

Rowe et al. (1975) and Johnson and Rowe (1977) investigated the characteristics of forest fires and related vegetation responses in the upper Mackenzie Valley and Caribou Range. The rapid response of permafrost to fire was seen in the form of silt and earth flows which developed within a year of the fires.

Wein et al. (1975) examined slumps in the area of the 1968 Inuvik fire and found that most of them had occurred since the fire. They concluded that fire does initiate slumps or soil flows when the landscape is unstable. Vehicle tracks caused more damage on burned areas than on unburned areas (Wein et al. 1975). First season active layer depths resulting from tracks on the burned areas increased about 10 cm (20%) in a black spruce community and almost 20 cm (25%) in a birch community.

Mackay (1977b) followed change in the active layer in the Inuvik fire which burnt an area of forest and tundra. The depth of thaw at five sites was measured in August of each year from 1968 to 1976. On a hillside site consisting of ridges and depressions, the active layer thickened rapidly for the first 4 or 5 years and was still increasing slightly after 8 years. The active layer on the hillside site under depressions thickened 57 cm to approximately 90 cm, and under ridges it thickened from 54 cm to approximately 115 cm. Due to its high ice content the hillside site has subsided nearly 50 cm. However, with time, as the vegetation changes and the permafrost aggrades upward, the ground surface will likely rise. Therefore, the long-term disturbance to the permafrost at this and other fire sites remains to be fully evaluated.

Viereck (1973), however, reported that depth of thaw under burned and unburned sites in four black spruce stands near Fairbanks was not significantly different (total thaw about 45 cm). Hall et al. (1978) noted a slight increase in thaw one month after a tundra fire in northwestern Alaska. In cottongrass tussock tundra at four fire sites in Canada and Alaska, Wein and Bliss (1973a) observed a 35-50% increase in thaw in June with an overall late summer increase of 15-25%. Cottongrass recovers rapidly after fire, and unless the organic mat has been consumed, long-lasting disturbance of cottongrass tundra in the form of thermokarst or erosion is unlikely. Haag and Bliss (1974a) reported results of an experimental controlled fire on tundra at Tuktoyaktuk. Thaw increased from 36 to 46 cm by the end of the first summer.

Recently, McKendrick and Mitchell (1978) reported that the soil did not warm appreciably during controlled burning of oil. In three burns at Palmer, Fairbanks and Prudhoe Bay, soil temperatures stayed below lethal levels for the vegetation at the 4-cm depth. Viereck (pers. comm.) similarly indicated that soil temperatures immediately after an experimental burn in the Fairbanks area did not increase below a depth of 15 cm. The heat of the Inuvik fire did not contribute to the initial thawing (Mackay 1977a).

Rouse and Mills (1977) summarized a three-year study of microclimatic changes which accompanied burning of lichen woodland in the Northwest Territory. Summertime soil temperatures were 3.0 to 5.5°C warmer in the burned areas; however, there was apparently no long-term soil warming. The soils in burned areas are drier and remain so for many decades. Kane et al. (1975), in a study of soil moisture and temperature near Fairbanks, concluded that the thermal and moisture regimes of soils undergo considerable alteration because of fire. These changes are related to long-term changes due to modification in the surface layers.

The rapidly burning fires on old lake beds and polygonal ground are unlikely to produce long-term disturbance since the underlying wet organic soils have not been drastically modified (Shilts 1975). The more intense and hot fires which do burn the peaty materials are likely to alter the depth and configuration of the permafrost surface. This is particularly so around mineral frost scars, where thaw increases adjacent to the scars. It has been suggested that the intensity of frost action and the formation of frost scars may be a function of the frequency of tundra fire (Viereck, pers. comm). Pettapiece (1974) described the role of fire in cyclic aspects of hummocky soils. The loss of the surface organic layer due to fire initially promotes the downward retreat of the ice-rich upper permafrost. A loss of volume creates settlement in the center of the hummock. Subsequently the increase in the vegetative mat results in an aggrading permafrost table, which in turn results in an elevation of the hummock.

CRYOGENIC PROCESSES AND REGIONAL DISTRIBUTION OF PERMAFROST IN THE USSR

· Human disturbance of permafrost terrain gives rise to cryogenic and other geological processes which alter the landscape in undesirable ways. The damage which results is generally slow to heal, a characteristic of the northern environment (Kriuchkov 1976). The cryogenic processes such as frost heaves, fractures and icings are associated with increased freezing of soils in permafrost areas. Thermokarst, thermal erosion and subsidence, solifluction, and landslides are associated with thawing. The specific causes and rates of cryogenic processes are dependent upon many environmental factors (Romanovskii 1978a).

The newest geocryologic map of the USSR, including the arctic shelf, provides the basis for delineating areas where cryogenic processes are probably active (Kudriavtsev et al. 1978b). Offshore over most of the arctic shelf and basin, permafrost is widespread, with the exception of the continental slope under 200-900 m of water and in zones influenced by the warming effects of discharges from large rivers. The thickness of the frozen sediments in the shelf area of deep water can be up to 30 m (Are 1978a).

In the southern part of the permafrost region of the USSR there is island permafrost. Farther north the size of these islands increases, as does the thickness of the frozen stratum. Its temperature is 0° to −2.0°C. In the northern regions there is continuous permafrost with temperatures −3° to below −15°C and thicknesses up to 500-700 m. The greatest thickness of ground with negative temperatures (800-1500 m) is to be found in the Paleozoic stratum of central Siberia, where ground containing supercooled salt solutions below 0°C underlies the frozen layer (Kudriavtsev 1978b). In the high altitude regions (Tian Shan, Pamiro-Alai) permafrost covers an area of more than 100,000 km^2. Sporadic permafrost begins to appear at altitudes of 2200-3200 m; at altitudes of 2700-3700 m islands of permafrost occur; discontinuous permafrost is to be found at 3200-4100 m; and continuous permafrost at altitudes above 3500-4400 m. The greatest permafrost zone thicknesses (more than 860 m) and the lowest negative temperatures (−19°C) are found in rock massifs (Gorbunov 1978). Significant depths of bedrock freezing are found in the Pai-Hoi ridge (Polar Urals), where the frozen layer may be up to 800 m thick (Oberman 1978).

The rates of seasonal thawing and freezing of soils to which cryogenic processes are closely related are found in the schematic map by Vtiurina and were also investigated by Cherniad'ev (1976). Cryogenic processes may exist beyond the southern limit of permafrost, which is not only sensitive to climate but to human disturbances (Makeev 1977). The cryogenic processes develop differently in various zones (polar deserts, tundra, taiga, forest-steppe and continental or maritime climates). The regional climate determines the features of the cryogenic processes in the northern permafrost zones, whereas meso- and microclimates are more influential in the southern and discontinuous zones (Gavrilova 1978).

The type and thickness of the organic cover greatly influence the depth of seasonal thawing. Research in northern Tyumen Oblast on seasonal thawing under various types of tundra vegetation indicated that a moss-lichen cover exerted the greatest influence on the thermal regime of the ground, whereas a sedge-sphagnum cover had the least influence (Skriabin 1978).

The presence of underground ice is the main condition necessary for large scale cryogenic processes such as the formation of thermokarst features and thermal erosion. The distribution of underground ice is irregular (Vtiurin 1978) with separate areas of sheet ice, ice wedges, and other types of ground ice. Ice wedges have the largest areal distribution (see Figure 1). The character of cryogenic processes depends on the relationship between the landscape components. The composition of the soils and their ice contents, the topography, and the climate are related to the microclimate, vegetation, snow cover, and ground temperature regimes. Human-induced changes in these regimes determine the character of the resulting technologically produced landscape (Balobaev 1978, Fel'dman 1977, Mel'nikov 1976, Mel'nikov and Tolstikhin 1974, Shvetsov 1973).

Cryogenic processes resulting from natural causes such as changes in climate, plant succession, and geomorphic processes take place slowly and can be measured over many years. Thermokarst in northern Yakutia has a long and complicated history (Gravis 1978, Konishchev 1974) and is related to cooling and warming during the Quaternary. New cryogenic processes occur in northern sections of West Siberia as a result of swamp formation in the taiga and its replacement by sparsely forested sphagnum and lichen bogs. Deep freezing occurs on the growing hillocky peat bogs which are more snow free as a result of wind exposure in these open areas. Soil temperatures are decreased by 4°C (Belopukhova et al. 1976).

Natural cryogenic processes have been investigated in detail: thermokarst (Gravis 1978, Romanovskii 1977, Shur 1974, 1977, Sukhodrovskii 1976); processes on slopes (Sukhodrovskii and Gravis 1976, Zhigarev 1975b); frost action (Grechishchev 1978, Podbornyi 1978; Romanovskii 1977b, 1978a, b, Romanovskii and Liebman 1975), frost heaving (Nevecheria 1975, Romanovskii 1978b) and gully formation (Kosov and Konstantinova 1975).

Human-caused surface disturbance increases the rate

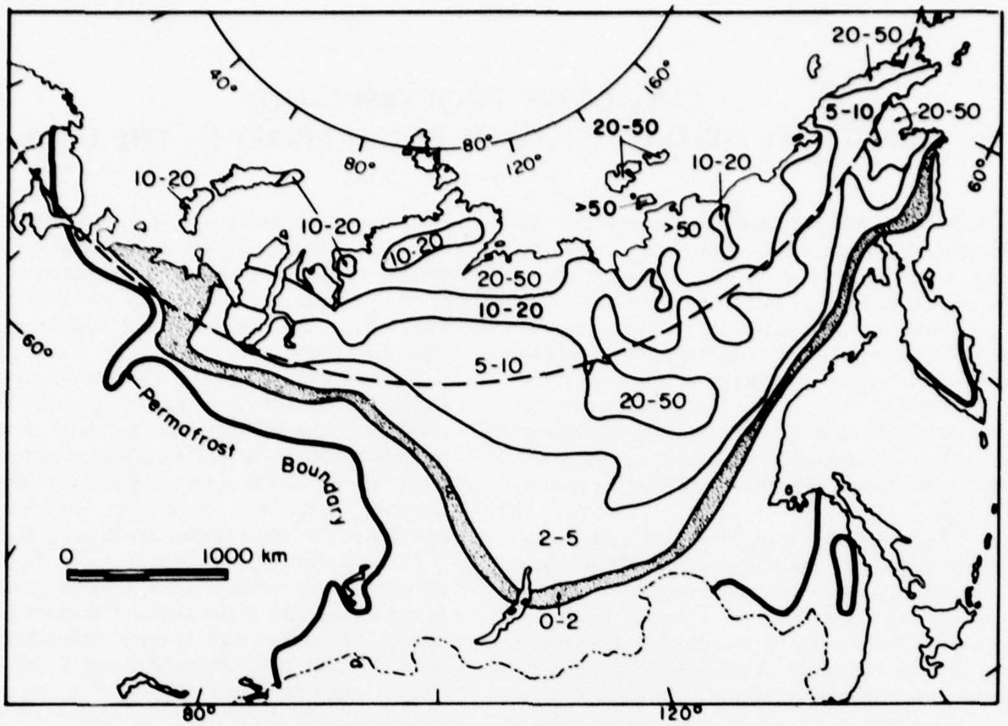

Figure 1. Ice wedge distribution in percent of area for permafrost regions of the USSR (Vtiurin 1975).

of cryogenic processes. After the active phase following disturbance, which usually takes 2-3 years and results in topographic changes, changes are more gradual and may cease after about 10 years. The result is the formation of a new landscape (Grave and Sukhodrovskii 1978, Grigor'ev 1977, Kriuchkov 1976, Mel'nikov et al. 1977).

The direct cause of changes in the cryogenic processes in permafrost regions is modification of the surface heat balance. Partial or complete removal of the surface organic layer in the northern section of West Siberia increased the radiation balance by 5-15%, the mean ground temperature by 0.7 to 2.0°C, and the depth of seasonal thaw by 2-3 times (Pavlov 1978). Human activity results in greater changes in the surface heat balance than do natural causes (Mel'nikov et al. 1977a, Sergeev and Skriabin 1978).

The modification in the surface heat balance can be either negative or positive and depends on the particular permafrost zone and the type of impact. Surface disturbance in one area can cause an increase in ground temperature, followed by the appearance or further development of thermokarst, thermal erosion and solifluction, while the same disturbance in another area can cause frost heaving, icings, and cracking of the ground (Alekseev 1977, Belopukhova et. al. 1976, Fel'dman 1977, Lisitsyna 1977, Makeev 1977, Moskalenko 1975a, b, c, Moskalenko et. al. 1978, Romanovskii 1978a, b, Romanovskii et al. 1978).

Human-induced cryogenic processes have not been well investigated. Their classification and some features have been investigated in a regional approach (Adushkinov and Borishenko 1975, Arkhangelov et al. 1975, Chizhov et al. 1977, Efimov and Efimova 1975, Kulakov 1977, Leshchikov 1975, Maksimova 1977b, Maksimova et al. 1975, Nevecheria et al. 1975, Neizvestnov and Postnov 1975, Poltev et al. 1975, 1978, Stepanov 1977).

HUMAN-INDUCED TERRAIN DISTURBANCE AND CHANGES IN GROUND TEMPERATURE REGIME

The principal types of disturbance, including the destruction of topography, can be treated as part of the study of the formation of human-induced landscapes. The specific features of these landscapes are determined by the type of disturbance, the consequent cryogenic and other geological processes, and the characteristics of the original landscape. There are only partial references to this subject in the literature (Ermakov et al. 1977, Kondrat'ev et al. 1977, Leshchikov 1975, Poltev et al. 1975, 1978, Serdiukova and Vnukov 1975, Serdiukova et al. 1975, Sokolov 1975, Sukhodol'skii, 1975).

The disturbance of plant and soil covers

The polar deserts have a very thin and discontinuous plant cover, with areas of exposed mineral soil that usually are larger than the areas covered by vegetation (Matveeva and Chernov 1976). Disturbance of this type of cover by vehicles or reindeer herds has little effect on the depth of summer thaw, and in spite of high ice content in the ground, little melting occurs. The main disturbance is destruction of reindeer pasture (Andreev 1977). The same is true in the taiga where damage to the moss cover leads to loss of plant cover in treeless sites (Belyi 1977).

In the forest-tundra and northern taiga zones (fluviolacustrine plains) of Western Siberia the removal of the surface moss cover from hummocky peat land and muskeg which are underlain by frozen sand and silts does not lead to significant increases in ground temperatures or depth of seasonal thaw. This is explained by the low thermal conductivity of the peat, which usually dries out at the beginning of the summer. However, once the peat cover is removed, the sands and silts thaw deeper, thermokarst occurs, and lakes and bogs develop (Moskalenko 1975b, c, Nevecheria et al. 1975, Slavin-Borovskii 1975).

Investigations from different locations in the tundra and forest-tundra of Western Siberia during 1974 and 1976 have shown that the differences in moisture content of the ground and the depths of seasonal thaw are not so much conditioned by zonal climatic factors as they are by ecological conditions. These ecological conditions are the factors which determine the degree to which vegetation and soil cover disturbance will affect ground temperatures, moisture and summer thaw (Table 2).

Removal of the tree cover in the southern taiga and forest-steppe zones of Western Siberia decreases the depth and increases the density of the snow cover on the treeless sites, which results in a lowering of the ground temperatures. Islands of permafrost develop and "short-term" permafrost appears where there was none previously. Landscapes are created with characteristic processes of frost heaving and frost cracking (Makeev 1977, Tshigir et al. 1977).

In both the tundra and taiga of Western Siberia, where removal of vegetation and surface soils exposes frozen sands, the newly thawed, dry sands are blown by strong winds, forming human-impacted landscapes termed "sandy arenas." The sand storms damage populated areas (Shilova and Mamaev 1977). Naturally occurring extensive areas of blowing sands or *tukulans* occur in central Yakutia (Shepelev 1976).

In the northeastern Siberian lowland, with its massive ice wedges, the disturbance and removal of the plant cover and soil mantle increase summer thaw, and thermokarst and thermal erosion are widespread. Hillocky terrain with water-filled depressions and cemetery mounds (*baydzherakh*) is nearly impassable and gullies form (Efimov and Efimova 1975, El'chaninov and Shor 1975b, Zhigarev 1975a, Tyrtikov 1975). The shores and slopes of thermokarst lakes and sea coasts formed from ground containing ice are also subject to erosion (Are 1978b, Troitskii 1977).

In the taiga of Central Yakutia, where there are extensive masses of ground ice, clearing of vegetation, removal of tree stumps and disturbance of the soil mantle cause thermokarst. This process is slowed by the hot and dry summer climate and is limited to the area in which the vegetation was damaged. The surfaces of the sites cleared for agriculture soon become hummocky and boggy (Zamolotchikova and Smirnova 1974). Systematic observations at various sites in the region around the city of Yakutsk (Zabolotnik 1978) have shown that clearing of trees while maintaining both the snow and moss cover results in considerable warming of the ground. Four years after forest removal, ground temperatures had increased by 1.3°C at the 3-m depth. However, simultaneous removal of the forest, moss and snow covers leads to considerable cooling of the ground. Over a four-year period of observation, ground temperatures decreased by 1.7°C in comparison with natural conditions.

In drained and dried sites, sodium sulfate and sodium chloride salinization of the soil frequently occurs and about 30% of the agricultural land becomes unusable (Elovskaia et al. 1977a, b). Where fire occurs and massive ground ice is present, "pyrogenic tundra" forms (Kriuchkov 1976, Kurbatskii 1977). In mountainous areas, altiplanation terraces become more active following the disturbance of the plant cover (Kudriavtsev et al. 1977).

Destruction of ground and underlying rock

Excavation during construction and mining, and building of dikes, embankments and spoil piles cause intensive surface disturbance. These activities influence all permafrost zones and particularly sites with high content of ground ice.

During open pit or underground mining and associated construction activities, not only are the soil and plant covers destroyed, but shocks and vibrations from machinery disturb soil structure. Runoff water from mining results in erosion. Changes in topography and the increased chemical and sediment loading of rivers and lakes lead to impacts far beyond the boundaries of direct activity. In areas with soils of high ice content, especially in northeastern USSR, human-impacted landscapes form consisting of cemetery mounds, landslides of thawed earth materials, and other forms of thermal denudation and erosion, and slopes are lowered (Zhigarev 1975a).

Waste rock piles formed during mining activities and construction of embankments are heat insulators. In areas where the permafrost temperatures are relatively high, taliks form within 2-3 years. Piles and embankments disrupt the hydrological regime of adjacent areas and stagnant surface waters accumulate. The taliks form as a result of stagnant waters which coalesce with those formed under the waste piles and embankments, and thermokarst may develop if sufficient ground ice is present.

Table 2. Temperature-moisture regime of soil and ground under natural and disturbed conditions (modified from Moshalenko and Shur 1978).

Natural ecological complex	*Avg ground temp (°C)*	*Avg moisture in 50-cm soil layer (mm)*	*Max summer thaw (m)*
Southern Tundra (1974)			
1 Spotty tundra on sandy loam deposits			
a Sandy loam spot	−6.2	179	1.15
b Grass-shrub cover	−5.7	167	1.06
2 Shrub-moss tundra on peaty sandy loam deposits	−6.8	193	0.52
3 Polygonal tundra on peaty sandy loam			
a Shrub-lichen-sphagnum polygon	−7.3	224	0.35
b Grass-sphagnum trough	−7.2	—	0.43
Forest Tundra (1976)			
4 Spotty polygonal tundra on sandy deposits			
a Sandy spot	—	35	1.8
b Shrub-lichen polygon	−1.3	49	1.7
5 Spotty larch shrub on peaty loam			
a Loamy spot	—	171	1.49
b Shrub-lichen cover	−2.3	165	1.3
c Loam with vegetation removed	—	160	1.62
d Peaty loam with vegetation removed	−2.5	172	1.52
Northern Taiga			
6. Shrub-sphagnum-lichen peat moss			
a Hummock	−0.8	260	0.63
b Depression between hummocks	—	285	0.57
c Same surface with vegetation removed	−0.8	248	0.7
7. Peat-mineral mound with shrub lichen cover			
a. Mound	−0.7	200	0.92
b. Depression	—	220	0.65
c. Same surface with vegetation removed			
Mound	−0.7	160	1.43
Depression	—	180	1.3

Human-impacted terrain, and specifically waste rock piles, is unsuitable for land use; it is also the cause of chemical pollution of water and requires restoration and rehabilitation (Bol'shakov 1975, El'chaninov and Shor 1975a, b, Krylov et al. 1975, Neizvestnov and Postnov 1975, Peretrukhin et al. 1975, Sever'ianov et al. 1975).

Long, deep quarries in the southern part of the permafrost zone are a source of new permafrost formation and accompanying cryogenic processes, if water does not accumulate in them (Klimovskii 1978).

Experience with coal mining operations in permafrost areas has shown the danger of icings and shaft cave-ins where the surface has collapsed to a depth of 60 m. Air and water which enter through the shaft lower the stability of the ground (Sever'ianov et al. 1975, Sever'ianov and Popov 1975). It has been shown that roof thaw depends on the number of galleries and the distance between them (Fedorov 1976).

The influence of urban development

Towns and villages represent a particular type of human-impacted terrain which results from very complex geological and engineering processes. A classification has been drawn up of factors related to human impact and conditions that influence the temperature regimes at the air/ground interface, and of ground waters in populated areas. Both direct and indirect factors that contribute to increasing or lowering the temperature are indicated (Kotlov 1977).

L.N. Khrustalev (1975) studied the influence of large buildings on changes in the geocryological conditions. In the northern and central permafrost zones, it was established that the properties of the snow cover exerted the greatest influence on heat exchange on ground that has been built upon. In southern regions, destruction of peat moss cover, use of artificial surfaces, and the distribution of buildings significantly influence the heat regime, since they change the conditions of moisture movement into the ground (Porkhaev and Shchelokov 1973). Changes in the thermal balance at the ground surface resulting from human impact in the city of Vorkuta led to partial degradation of permafrost for 80-90% of the region (Gorbacheva 1975). Within the main areas of permafrost, towns and villages generally lower the

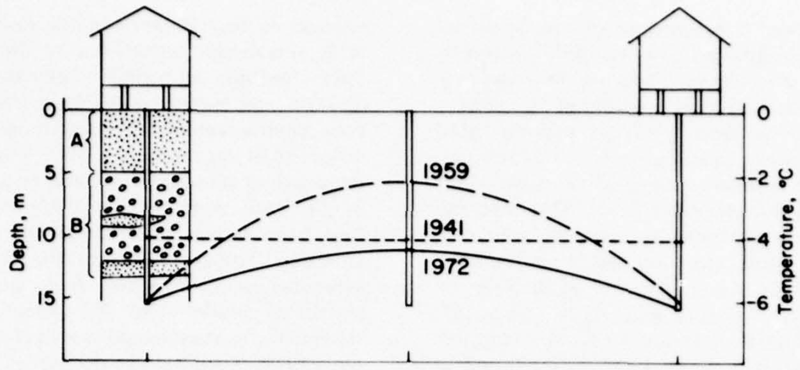

Figure 2. Idealized cross section of buildings and road in Norilsk showing the changes in ground temperature resulting primarily from differences in winter snow accumulation and related methods of snow removal. A is fine icy sand with moisture of 25%, and B is clayey loam gravel with sand lenses. (Bobov and Lapochkin 1974.)

ground temperature (Porkhaev and Shchelokov 1973). Long-term measurements of ground temperature in Norilsk began in the tundra prior to construction and were then taken at various sites and different times as the city building progressed. Three to nine years after building commenced, ground temperatures in the city rose, but 19 to 30 years later they were lower than they were before development (Figure 2). The reason for the decrease was increased removal of snow within the city area when mechanization was introduced (1950-60). Until that time, snow was removed manually and remained in the yards (Bobov and Lapochkin 1974).

In Yakutsk, apart from decreases in ground temperature, particularly below old sections of the city, intensive salinization of groundwater and of the silty loam soils by chlorides of sodium and magnesium has been observed as a result of the penetration of saline water of less than 0°C (about 100 grams per liter) into the active layer and taliks below lakes. Salinization is associated with higher rates of evaporation and low precipitation during the hot summers in a city with insufficient drainage and other amenities (Anisimova 1975).

FORECASTING, MODELING, AND EVALUATION OF TERRAIN SENSITIVITY

The problem of geocryological forecasting, which should be considered as part of ecological forecasting, is very complicated. Most of the investigations represent individual solutions that are related to specific types of construction and that have been based on limited evaluations of isolated geocryological features of the natural environment (Kudriavtsev et al. 1978d, Shvetsov et al. 1973). The prediction of human impact is important to environmental protection (Kondrat'eva 1978, Maksimova 1977a). Working out a theory for human-impact forecasting is a very complicated matter. The thermal regime of the ground and fluctuations in the depth of seasonal freezing and thawing are of great importance in forecasting these processes. Phase transitions of water play the greatest role in these cryogenic processes. It has been established that albedo and radiation balance are the major factors in determining the energy budget of natural terrain. Relationships between the radiation budget and the mean annual temperature of the ground have been established (Pavlov 1975, 1978a, b).

The changes in the temperature regime of ground of various compositions and thermal conductivity and under various geological conditions are determined by the structure of surface heat balance (Balobaev 1974, 1978, Dostovalov 1978, Kondra'teva 1978, Moskalenko 1975c). G.M. Fel'dman (1977), following the ideas of V.A. Kudriavtsev (Kudriavtsev 1974, 1978, Kudriavtsev and Maksimova 1978, Melamed and Medvedev 1974), has developed techniques for forecasting the temperature regime of the upper layer of permafrost in relation to specific geological and geographical conditions. There are various possible approaches for conducting investigations at a particular building site (Alekseev 1977, Garagulia et al. 1975, Konstantinov et al. 1977, Kulakov 1977, Nevecheria 1975, Peretrukhin 1975, 1978).

Geological surveys furnish much of the information necessary for qualitative and quantitative forecasting (Kudriavtsev and Maksimova 1978, Kudriavtsev et al. 1978c). As a result of these surveys, an engineering-geological map of permafrost is prepared and predictions of changes to the natural environment and a forecast map or chart are compiled. A regional classification of soil and rock types and a comprehensive land use evaluation of natural and human impact development have been prepared (Kudriavtsev et al. 1978a, d, Badu and Trofimov 1977, Veisman 1977, Gorbylev et al. 1977, Mel'nikov et al. 1978, Nevecheria and Moskalenko 1977, Nefedova and Chizhov 1975).

In order to accelerate the investigation of new areas that are being considered for development, the method of "preconstruction impact studies" has been proposed. On the basis of surveys at scales of 1:100,000 and 1:200,000, an evaluation of permafrost conditions is made, and the terrain sensitivity resulting from damage

to the vegetation cover, to excavation, and to the warming influence of buildings is evaluated. Optimum building methods are chosen, bearing in mind environmental protection measures (Baulin et al. 1978).

Methods have been developed for making rapid engineering and geocryological surveys in oil- and gas-bearing areas and pipeline routes of northern West Siberia (Mel'nikov 1973, Mel'nikov et al. 1974). Most important is the landscape indicator method, which includes widespread application of aerial photography and topographic maps. An example of evaluating the territorial complexity of a gas pipeline route is presented in a graphic model of the gas line in relation to landscape features (Mel'nikov et al. 1975). Compilation of the forecast mapping approaches for the regions of the Poluy-Nadym and Pur-Nadym in Western Siberia have been presented (Mel'nikov et al. 1978). Methods for interpretation and application of aerial and satellite photography, including spectrazonal photography, are being perfected (Gavrilov and Ershov 1977, Gavrilov et al. 1978, Eliseev 1977, Lynov et al. 1977).

Experimental application of thermal aerial photography in permafrost regions produced promising results for mapping geocryological features (Gornyi and Shilin 1978).

An indicator-interpretive scheme has been compiled on the basis of research carried out in the northern taiga and forest-tundra landscapes of northern West Siberia. The scheme includes interpretive features for 16 terrain indicators and their corresponding geocryological conditions (Moskalenko 1975a).

Information received from permafrost surveys is used to define characteristics and conditions when performing quantitative forecasting which includes mathematical and physical modeling. Mathematical models of thawing and freezing processes employ the Stefan solution. Computer modeling of this problem has been suggested and it has good prospects for solving multi-dimensional problems (Melamed and Medvedev 1974, Kudriavtsev 1974). Kudriavtsev has derived a formula for heat circulation within the layer of annual temperature fluctuation which takes into account phase transitions of water during seasonal freezing. It is based on the annual temperature at the bottom of the freeze-thaw layer, and the composition and moisture content of the soil (Melamed 1978). G.M. Fel'dman has proposed solutions that more closely approximate actual environmental conditions (Fel'dman 1973, 1977). Through experimental research, he derived the quantitative dependence of seasonal freeze-thaw depth, temperature of the frozen ground, and heat circulation in the ground on the combined parameters of air temperature and the composition and properties of the snow, vegetative cover and ground (Fel'dman 1977). Thermal conductivity of tundra cover in its natural and disturbed states has been researched by Mandarov and Skriabin (1978). Similar quantitative relationships have been published for Western Siberia (Grechishchev et al. 1975).

A model has been proposed for calculating ground temperature and summer thaw depth in relation to changes in heat balance of the diurnal surface conditions; this model permits one to study the influence of the meteorological regime on geocryological conditions (Palagin and Natanzow 1975). A model and algorithm have been developed for determining the quantitative influence of vegetation and snow cover disturbances on the depth of seasonal thaw, and on ground temperature in the BAM zone (Pal'kin 1975). Analytical solutions have been derived for areas disturbed during road construction (Savko 1978). For the BAM zone forecast estimates or calculations have been made using a statistical model and 1-2 dimensional calculation scheme for heat exchange in soils (Tutkevich and Gorodnova 1977). A solution to the Stefan problem is given in order to choose a method for thermal amelioration of frozen ground (Smorygin and Fandeev 1977).

Analytical solutions are available for predicting the results of cryogenic processes: reworking of shores of lakes and reservoirs (Balobaev and Shastkevich 1974, Gogolev 1977, Savko 1977, Tomirdiaro and Riabchuk 1974), icings or *naled'* (Sokolov 1977), slope processes (Kudriavtsev et al. 1977, Chubarova and Lavrent'eva 1977) and thermokarst (Fel'dman 1977, Shur 1977).

In contrast to the existing solutions to the problem of ground freezing under a snow cover, a different method of solving the problem has been proposed; it takes into account the dependency of the thermal conductivity of snow on temperature. A computer program has been developed for three- and four-layered media using the EVM-M-222 computer (Shipitsina 1978). Solutions to problems concerned with the temperature field of frozen ground around mines and mine shafts have been studied and calculations have been made (Fedorov 1976).

Critical changes of parameters of such systems as soil-frozen ground and thawed ground-groundwater due to industrial development of the territory, and catastrophic changes due to disturbance of the natural environment, have been studied from the thermophysical aspect (Khrustalev 1975).

Physical modeling using electro- and hydrointegrators is being widely implemented in forecasting. This type of modeling has been used for environmental protection purposes in one of West Siberia's regions to evaluate methods for improving water quality (Novikov 1977) and to determine the influence of surface cover and topography on the freezing and thawing of the ground (Ershov 1971a, b, Ershov et al. 1978).

Techniques for evaluating terrain sensitivity to technological impact are being developed. It has been suggested that terrain sensitivity should be estimated on engineering-geological maps (Demidiuk 1977), landform-permafrost maps (Lynov et al. 1977), ice-content maps (Lur'e 1977), and on regionalization maps according to type and intensity of thermokarst, thermal erosion and frost heaving (Chizhov et al. 1977, Smirnov et al. 1975, Stepanov 1977). Systematic photogeological mapping of the territories under development is in progress (Eliseev 1977).

It is recommended that estimates of rates of cryogenic process development and landscape changes be made, and that the effectiveness of environmental protection measures in regions of planned pipeline routes be evaluated. Pipeline route conditions are considered under two different categories: 1) complex, where there is frozen ground, and the temperature of the discontinuous permafrost is high, and 2) simple, where ice content is low and the temperature of the permafrost is low (Baulin et al. 1978). L.N. Maksimova (1977a) has presented the following classification for the engineering-geological evaluation of permafrost areas under development:

1. Regions where development disturbs permafrost conditions and ecological systems, and irreversible cryogenic processes are set into motion, disturbing existing landforms.
2. Regions where development does not cause catastrophic changes in landscape, and where it is possible to partially reestablish natural processes, through natural or artificial means.
3. Regions where changes in permafrost conditions lead to favorable changes in the geological environment.
4. Regions where changes in permafrost conditions have practically no effect on the geological environment.

A ten-point scale of probability for activating cryogenic processes as a result of changes in surface heat balance resulting from territorial development is suggested. However, factual observations necessary for developing this sensitivity scale are insufficient at present (Shur 1977).

A territorial evaluation has been made according to the degree of complexity of engineering undertakings needed to improve permafrost-engineering-geological conditions (Gavrilov et al. 1978). Three categories have been designated:

1. Those conditions that do not need complex measures.
2. Those requiring complex measures.
3. Those which require extremely complex measures.

PROTECTION OF TERRAIN DURING DEVELOPMENT

The main protection measures emphasize prevention of the thawing of permafrost. These measures include thermal and hydro amelioration of soils, biological recultivation where the surface was disturbed during development, and other measures for specific types of developmental activity such as mining, landfill and agricultural development.

Methods have been proposed for ground heat amelioration, control of ice sublimation and desublimation in frozen soils by means of changes in gas medium parameters, and controlled changes on the surface of ground masses (organic film, surface coating) (Ershov et al. 1974, 1978).

Practical measures for environmental protection have been developed during the construction and operation of trunk pipelines, mostly in Western Siberia. Environmental protection measures must adhere to the following requirements: excavation and pipelaying operations should be carried out during the period of stable negative air temperatures; tree stump and root removal is prohibited in areas of high ice content; traffic is possible only with maximum maintenance of the vegetative and soil covers and without disturbance of the soil surface on the right-of-way (Bol'shakov 1975, Ivanov and Friman 1975, Mikhailovskii and Lolua 1975, Serdiukova and Vnukov 1975, Serdiukova et al. 1975). The use of natural and artificial insulating materials is recommended for covering areas that have been denuded of vegetation or soil cover and leveled during construction (Mikhailov 1975). Complex areas requiring costly environmental work and materials are best avoided during pipe-laying due to economic considerations (Sukhodol'skii 1975). During road construction, apart from the above-mentioned measures, it is recommended that fill be placed over the natural vegetation and organic layer or onto artificial thermo-insulation (synthetics, peat, slag, wood flooring). It is desirable to paint the fill surface white (Bol'shakov 1975, Kaganovskaia 1975).

Special techniques and technology are recommended during mining activity such as excavating the producing strata and reinforcing the roofing of galleries and shafts. To prevent surface subsidence over mine shafts it is recommended to use short-face systems (of mining) and to plug the worked-out sections (Fedorov 1976, Krylov et al. 1975, Sever'ianov et al. 1975).

Areas with near-surface, ice-rich soils are considered to be entirely unsuitable for agricultural development within the taiga region if they require uprooting of trees and plowing. Apart from bog formation that may take place, the surface that has been cleared of trees and plowed becomes hummocky as a result of uneven subsidence. Drainage can be introduced where more homogeneous subsidence due to thaw occurs (Vidiunina and Khudiakov 1974). However, drainage is not always effective in cold climate and permafrost areas. Wide experience with drainage and flushing of saline soils has been gained in Central Yakutia (Elovskaia et al. 1977b).

In order to control permafrost conditions in agricultural areas so that cryogenic process development may be avoided and to increase soil fertility, thermal and water amelioration techniques are introduced. Significant amongst these are snow enhancement techniques, which, depending on the conditions, either allow thawing of the underlying permafrost or prevent new permafrost aggradation and pereletok formation. The regulation of snow cover in West Siberia serves as a basis for modifying the temperature regime and freezing and thawing of the soils. Recommendations have been developed for snow retention in fields and a system of techniques for thermal improvement of areas with varying natural conditions has been developed in West Siberia (Tshigir et al. 1977).

Table 3. Depth (meters) of seasonal thaw of sandy loam in Yakutia, under various surface modifications (modified from Pavlov 1978a, b).

Type of cover	*1972*	*1973*	*1974*	*1975*	*1976*
Natural	1.89	1.99	1.80	1.85	1.83
Wooden paneling	1.75	1.78	—	—	—
Wooden panel and foam insulation layer (1 cm)	—	—	0.64	0.73	0.63
Foam insulation (7 cm)	1.01	1.09	0.97	1.00	—
Foam insulation (20 cm)	—	0.42	0.35	0.39	—
Foam insulation (30 cm)	—	—	—	—	0.26

A scheme for land reclamation of Far Northern regions has been developed that holds promise for the future. It includes techniques of drying, irrigation, erosion control, and cultivation among others (Kriuchkov 1977).

Irrigation and drainage techniques for agricultural land in the permafrost zone are treated in numerous papers (Bogushevskii 1977, Elovskaia et al. 1977a, Gavril'ev and Mandarov 1976, Kamenskii 1976, Kriuchkov 1977, Lomakin et al. 1977). Other papers deal with artificial surface cover for purposes of temperature regime control and regulating of the thawing and freezing of soils in the permafrost regions (Demchenko 1978, Pavlov 1978a, Rashkin and Shuvalov 1970, Skriabin 1976, Smorygin and Vediaev 1977, Smorygin et al. 1978).

Several synthetic and natural materials have been tested for protecting soil from thaw. Long-term research in Yakutia and in the northern Tyumen has indicated that foam insulation has high insulating properties compared to other materials, particularly wood paneling (Table 3). The relationship of thaw depths beneath a foam insulation covering of varying thickness and under natural conditions was presented and a formula was suggested for the corresponding calculation (Pavlov 1978a, b). An approximate method for calculating ground thaw dynamics under the insulating layer has been developed using the EVM M-222 and different combinations of insulating layer properties and ground and ambient conditions (Demchenko 1978).

The effectiveness of a water-air foam as a heat insulator is being investigated (Smorygin et al. 1978). Synthetic transparent film is used to increase thawing of frozen soils. A model has been developed which will allow one to compute the ratios of thaw and freeze depth under various plastic film covers in order to determine the optimal time span required to cover the ground and to define how soils will thaw under the film as a result of changes in solar radiation. For more practical application, graphs and charts have been developed (Smorygin and Vediaev 1977). Field observations have shown that the film coverings raise ground temperature by 4 to 4.5°C, speed up the date of onset of thaw by 15 to 20 days, and increase the depth of summer thaw by 0.5 to 1.5 m (Rashkin and Shuvalov 1970, Skriabin 1976).

One of the measures used to restore the disturbances caused during development of territories is the recultivation of vegetation and restoration of terrain. These measures are not only of technical consideration—slope stabilization and recovery of vegetation to favorably affect the ground thermal regime—but are also of aesthetic importance. Difficulties of recultivation are, to a great extent, associated with the very slow natural recovery process of vegetation in the North.

Moss-lichen cover damaged by reindeer movement or destroyed by man is restored only after several decades. Partial meadow formation in denuded sites is arrested after a few years as a result of increased moss and shrub growth and bog formation (Kriuchkov 1977, Vital' 1975). Such phenomena have been observed in the tundra on the bottom of lake basins which have been drained in order to induce meadow formation (Tomirdiarov 1975). In Chukotka, the slow and partial regrowth of grasses on drained basins started to slow down after seven years because of moss growth and permafrost aggradation (Tatarchenkov 1977).

In northern West Siberia grass-moss bogs are the more quickly rejuvenated areas; it is here that bog formation increases when surface cover is disturbed. Shrub-lichen communities of flat peatlands are more slowly restored. Where soil cover is maintained, cloudberries, *Ledum* and cottongrass will grow back within 3 or 4 years. In cases where the peat layer is damaged and thermokarst depressions appear, grass-moss communities will develop. Vegetation, practically speaking, does not regrow on forest-covered hillocks and ridges underlain by frozen sands following the removal of the forest shrubs and peaty horizon. In order to accelerate and maintain growth of the recolonizing vegetation, special agrothermal techniques are applied (Bol'shakov 1975, Ivanov and Friman 1975, Liverovskaia 1975, Mikhailovskii and Lolua 1975, Serdiukova and Vnukov 1975, Serdiukova et al. 1975). In addition, problems of recultivation of human-impacted landscapes have been investigated (Kolesnikov 1974, Potemkin 1975, Razumovskii 1975, Smolianitskii 1976, Shcherbatenko and Kandrashin 1977 and Trofimov 1974).

A regional scheme has been developed for recultivation of impacted areas of Siberia and the Far East. Each zone is characterized by a description of its type of impacted terrain and the type of recultivation to be performed (Ragim-Zade and Trofimov 1977). On the basis of investigations into human impact on the natural complexes of Siberia, studies on the resistance to various levels of disturbance, and their influence on ecological conditions of human life, environmental protection programs have been developed, including recultivation. The optimal scheduling of work has also been considered (Ragin-Zade and Trofimov 1977).

In summary it is possible to classify human-induced terrain disturbance according to type and cause (Shur 1977, Smirnov et al. 1975, Trush and Chizhov 1977). These types, causes, sensitivities, and recommendations for environmental protection and recovery are presented in Table 4.

Table 4. Main types of human-induced terrain disturbances in permafrost regions of USSR, their causes and probable consequences, and general recommendations for environmental protection measures, depending on the surface sensitivity and type of disturbance (1, 2, 3). Based on N.A. Grave (in Gerasimov, in press).

Type of disturbance	*Causes of disturbance*	*Probable consequences of disturbance (according to region's sensitivity)*	*Recommended measures for environmental protection*
I: Compaction and damage to vegetative cover.	Movement of heavy vehicles, particularly in summer; intensive reindeer pasturing; light construction activities.	1 Development of thermokarst-eroded relief with "sunken" lake depressions and gullies. Thermal abrasion of shorelines.	(1) Limitation and regulation of vehicle movement and reindeer grazing; improvement of drainage; filling of upper reaches of gullies; thermo-insulation of surface cover; recultivation.
		2 Appearance of boggy depressions and eroded ditches within boundaries of disturbance.	(2) Regulation of vehicle movement and reindeer grazing; recultivation.
		3 Appearance of small boggy depresssions and ground slumping, restricted to area disturbed.	(3) Recultivation.
II: Destruction of vegetation cover; felling and removal of trees.	Intensive movement of heavy vehicles, especially in summer; drilling and exploration of deep wells; preparing right-of-ways for "linear" construction; fires.	1 See I-1.	(1) See I(1).
		2 In taiga regions of central Yakutia thermokarst subsidence within boundaries of damage. Rock streams and solifluction development on slopes. Increased ground freezing, frost heaving and crack formation of soil without thermokarst.	(2) Insulation of cover; recultivation.
		3 Localized bog formation; soil slumping.	(3) Improvement of drainage; recultivation.
III: Destruction of plant and soil covers, including peat lands; removal of tree stumps; exposure of mineral soil.	Intensive construction; surface grading; clearing for agricultural use.	1 See I-1.	(1) See I(1); winter work preferable; main construction should take place in winter and early spring when clearing forest for agricultural purposes; avoidance of areas of ground ice occurrence; local thermal insulation; drainage; recultivation.
		2 Thermokarst-bog depressions and lakes within limits of destruction. In northern section of West Siberia appearance of "sand arenas." In taiga and forest-stepped regions of West Siberia see II-2.	(2) See II(3); rapid land improvement and recultivation.
		3 Bog formation; appearance and increased development of solifluction and rock streams on slopes.	(3) See II(3).
IV: Excavating and stockpiling of soil and sediment; placement of embankments and pads.	*Intensive construction; surface grading; drainage and irrigation ditches; open-pit mining; dredging in rivers.*	1 See I-1.	(1) See III(1); placement of fill over vegetation cover; installation of artificial thermo-insulation layer; drainage system for adjacent areas.

Table 4 (cont'd). Main types of human-induced terrain disturbances in permafrost regions of USSR, their causes and probable consequences, and general recommendations for environmental protection measures, depending on the surface sensitivity and type of disturbance (1, 2, 3) Based on N.A. Grave (in Gerasimov, in press).

Type of disturbance	*Causes of disturbance*	*Probable consequences of disturbance (according to region's sensitivity)*	*Recommended measures for environmental protection*
		2 See I-1	(2) Drainage and recultivation
		3 Bog formation between dredge piles on fine-grained soils	(3) If possible, quick reclamation, covering with organic layer
		In southern regions of permafrost increased freezing of walls and trench bottoms and ditches and permafrost forms if no water present. Development of heaving	
V. Destruction of mineral rock masses with partial removal of ore, including pumping of water, oil, gas	Underground mining of minerals; pumping of water and hydrocarbons	1 See IV-1; subsidence, deep cave-ins of surface overlying mines	(1) Use of shallow-mining systems with refilling of mined space
		2 See IV-2; subsidence, cave-ins of surface	(2) Special measures for reinforcing ceilings of mines and back-filling
		3 See IV-3; in some cases possible cave-ins and subsidence due to thaw in mine ceiling, possible also to increase freezing of ceiling and walls of mine to increase stability strength	(3) Under certain conditions induced or forced cold air in shaft, recultivation and surface and ground water drainage

1 Region of extreme sensitivity:
Intensive processes of thermokarst, thermal erosion forming "sunken" lakes and gullies resulting from outside the limits of the slightest surface disturbance.
2 Region of average sensitivity:
Not so intensive; disturbances remaining within the boundaries of the slightest surface disturbances.
3 Region of low sensitivity:
Weak subsidence with formation of bogs and slope movement phenomena within the area of disturbance.

CONCLUSIONS AND RECOMMENDATIONS

A large number of observations on the response of permafrost terrain to human-related activities and natural processes have been reported. The majority of the North American investigations were undertaken in the Mackenzie Valley and a lesser number in the Arctic Islands and Alaska. Computer modeling of natural and impact processes and related field measurements are providing insight into the relationships of coupled moisture and heat flow. Approaches to terrain sensitivity analyses have been undertaken and partially evaluated.

Active, natural processes occur primarily in the summer and provide useful indicators of potential terrain hazards. These include thermokarst and thermal and hydraulic erosion processes on permafrost terrain containing large quantities of ground ice and river bank erosion and soil slumping and flows on steeper terrain. Fire as a natural agent of thermal disturbance generally results in thickening of the active layer over a number of years and greater incidence of slope failure.

Human-induced disturbances are limited to specific areas of construction or urban areas and linear transportation routes. The intensity and time of disturbance and terrain properties control the response of the terrain to disturbance. Disturbances resulting from summer activities have greater physical and visual impacts than activities occurring in the winter. Most disturbances caused by surface activities in the summer are no longer permitted due to restrictions of access. However, past disturbances are still active and provide useful information on questions of long-term stability and recovery. Off-road vehicle traffic on low pressure or air cushion tires in the summer produces some immediate visual impact and considerably less thermal or physical disturbance compared to more conventional tracked vehicles. Spillage of hydrocarbons on permafrost terrain seems not to cause major thermal disruption; however, the

saturated soils and the underlying impermeable permafrost may facilitate movement of the oil downslope and thereby increase the area of impact.

Observations on natural and disturbed active layer thicknesses, thermokarst features, ice wedges, and mass movements are leading to a better understanding and predictive capability of the geographic consequences of disturbance. Response to disturbance by active layer thickening is greater in the warmer discontinuous permafrost zone compared to the colder conditions that exist, for instance, in the Arctic Islands. The use of terrain disturbance as an indicator of climatic change has much to offer. For instance, deterioration of the permafrost at its southern boundary is obvious from the appearance of thermokarst features. Activity and stratigraphy of ice wedges and other ground patterns provide more subtle indications of change.

Some recommendations for continued research are:

1. Continue observations on past disturbances in order to establish the time required to reach the maximum level of disturbance and rate of recovery.

2. Continue development and field testing of terrain sensitivity mapping at several scales and compare approaches and synthesize results between North America and the USSR.

3. Undertake comprehensive geomorphic and regional geothermal investigations for purposes of establishing the stability of permafrost conditions under natural climatic change.

4. Continue the development of computer modeling of coupled heat-moisture flow and field validation in order to anticipate the results of human and natural activities.

5. Establish long-term monitoring observations to confirm or invalidate prior environmental assessments and impact prediction of large engineering projects such as dams, pipelines, and highways (National Academy of Sciences 1975).

6. Continue research to develop improved methods and guidelines of environmental protection and restoration of permafrost terrain.

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APPENDIX I: SYNOPSIS OF TEMPERATURE LITERATURE ON LAND-BASED AND SUBSEA PERMAFROST, MICROCLIMATE AND ENERGY BALANCE, AND RELATED MODELING LITERATURE

Reference	*Location*	*Synopsis*
		Land-Based Permafrost (Non-alpine)
Brown (1975)	Quebec and Newfoundland	Permafrost is patchy and restricted mostly to peaty areas between the −1.1°C and −3.9°C mean annual air temperature isotherms. Permafrost is widespread north of the −3.0°C isotherm.
Brown (1977)	Devon Island	An upland plateau site yielded the highest mean annual temperature (−14.6°C) and a limestone site near the coast the lowest (−16.8°C).
Brown (1978)	Manitoba and Keewatin	Reports are given on active layer and ground temperature data to depth of 15 m.
Decker and Bucher (1977)	Antarctica	Permafrost thickness is up to 970 m and the temperature in the upper 50 m is as low as −24°C.
Hollingshead et al. (1978)	Mackenzie Delta	Permafrost beneath the channels of the Mackenzie Delta is apparently aggrading in water depths of less than 85 cm.
Isaacs (1974)	Fort Good — Norman Wells	Mean annual temperatures in the upper several meters are generally warmer than at depth, suggesting a climatic warming trend.
Judge (1973)	Mackenzie Valley	Detailed information on the thermal regime is given and the role of snow in maintaining high ground temperature is identified as extremely significant.
Judge (1977)	Devon Island	Based on Brown (1977), the range of thickness of permafrost on Devon Island is 210 m in coastal areas and 659 m on adjacent uplands.
Mackay (1975)	Mackenzie Valley	Mean annual ground temperature increased 3°C from the late 1800s to the 1940s, with a possible 1°C decrease since. The warming has resulted in disappearance of permafrost in many areas of the upper Mackenzie Valley.
Taylor and Judge (1976a,b)	Arctic and Subarctic Canada	Based on temperature measurements, equilibrium conditions were estimated and thicknesses of permafrost are given. Arctic Islands over 700 m, Mackenzie Valley 300-600 m on east side, <150 m on younger west side.
		Land-Based Permafrost (Alpine)
Barsch (1978) and Haeberli (1978)	Alps	Permafrost is continuous above 3500 m, which is equivalent to a mean annual temperature of −8.5°C; the lower limit of active rock glacier is −2°C MAT.
Fujii (1978)	Northern Hemisphere	Distribution of alpine permafrost is given and total area estimated at 2.3×10^6 km². This occurrence of alpine permafrost is related to the coldest and warmest months' mean temperature.
Fujii and Higuchi (1976)	Himalayas	Permafrost occurs above 4900-5000 m.

Reference	Location	Synopsis
		Land-Based Permafrost (Alpine) (cont'd)
Gorbunov (1978)	World-wide	Two types, oceanic and continental, and eight categories of geocryological belts are distinguished. Permafrost occurs above snowline in the oceanic type and below snowline in the continental type. Permafrost occupies an estimated 1,500,000 km² in mountains, excluding the uplands of eastern Siberia and the Far East.
Harris and Brown (1978)	Canadian Rocky Mountains	Temperatures of −1.0° to −1.5°C to depths of 15-30 m are reported, with thickness in excess of 100 m.
Ives (1974)	U.S. Rocky Mountains	Continuous permafrost exists above 4100-4400 m, which is equivalent to an extrapolated minimum mean annual temperature of −9°C.
Woodcock (1974)	Mauna Kea, Hawaii	Permafrost occurs to a depth of 10 m at an altitude of 4140 m.
		Subsea Permafrost
Chamberlain, et al. (1978)	Prudhoe Bay	The physical properties and temperature profiles of shallow subsea permafrost are reported including the occurrence of an overconsolidated marine clay.
Harrison and Osterkamp (1976)	Prudhoe Bay, Alaska	A coupled heat- and salt-transport model is proposed.
Hunter et al. (1976)	Canadian Beaufort Sea Shelf	Beyond the warming influence of the Mackenzie outflow, the maximum thickness of permafrost in equilibrium with the surface temperature ranges from 25 to 75 m.
Judge (1974)	Canadian Arctic	Equilibrium permafrost is widespread off the Arctic Islands. In water more than 100 m deep, areas which were unglaciated and which have undergone little isostatic movement probably contain thick remnants of subsea permafrost.
Lachenbruch and Marshall (1977)	Prudhoe Bay, Alaska	A simplified analysis of the near-shore thermal conditions is presented in two cases: 1) Permafrost thaws progressively downward from the sea bed and eventually disappears. 2) Permafrost persists near the sea bed in shallow water that freezes to the bottom seasonally. It requires 1800 years for temperatures to become nearly uniform following inundation.
Lewellen (1977)	Barrow, Alaska	Temperature profiles from varying distances offshore range from −8°C to <0.5°C; the influence of a barrier island on temperatures is discussed.
National Academy of Sciences (1976)	North America	Problems and priorities for research in the offshore permafrost environment are reviewed, particularly for northwestern North America.
Osterkamp and Harrison (1977)	Prudhoe Bay, Alaska	Sea bed temperatures increase from −3.4°C 203 m offshore to <1°C several meters offshore.
Raj and Judge (1977)	Mackenzie-Beaufort Sea	A coupled two-dimensional, heat-mass flow model predicts relict permafrost is probably found in water depths of 60-90 m; in shallow water (<20 m) permafrost is degrading from both the top and bottom; in deeper water (>20 m) it is degrading at depth and may be aggrading near the surface.

Reference	Location	Synopsis
		Microclimate and Energy Balance
Addison (1975)	Queen Elizabeth Island, Canada	Microenvironment, energy and water regimes of both natural and disturbed surfaces of two plant communities were determined.
Beattie et al. (1973)	Tununuk, Canada	Energy budgets over disturbed and undisturbed terrain and their relation to the Muskeg Research Institute terrain disturbance classification system are evaluated.
Courtin and Labine (1977)	Devon Island, Canada	The descriptive microclimatology and an evaluation of the energy inputs are given based on data from 12 sites on the Truelove Lowlands and adjacent plateau.
Gray et al. (1974)	Tuktoyaktuk, Canada	Methods to evaluate the energy budgets were developed and data are given for different levels of disturbance.
Guymon (1975, 1976)	Barrow and Fairbanks, Alaska	Field measurements of soil moisture, pressure and temperature were made and seasonal patterns of soil moisture regime are discussed.
Haag and Bliss (1974a)	Tuktoyaktuk, Canada	Energy components for undisturbed upland tundra and disturbed areas including winter roads, oil spills, fires and revegetated sites are analyzed.
Haag and Bliss (1974b)	Norman Wells, Canada	The influence of local forest cover and seismic line on energy exchange and depth of thaw are evaluated.
Haugen, et al. (1976)	Atkasook, Alaska	Air, surface and soil temperatures in tussocks, between tussocks, and in a pond were monitored for summer 1975 and multiple regression analyses performed to obtain relationships among temperature parameters.
LeDrew (1975)	Niwot Ridge, Colorado	The surface energy balance of alpine tundra is determined and an empirical formula for evapotranspiration is derived.
Luthin and Guymon (1974)	Fairbanks, Alaska	Summer soil moisture and temperature data under different vegetation were obtained and a conceptual model of drainage, vegetation cover, and thermal regime proposed.
Mackay and Mackay (1974)	Gary Island, Canada	Regression equations for influence of snow depth on ground temperature at 90 cm are estimated based on 1968-1973 data base; snow cover is probably a major determinant in permafrost depth.
Maykut and Church (1973)	Barrow, Alaska	Monthly and annual averages of incoming shortwave radiation, albedo, incoming longwave radiation and net total radiation are reported and analyzed for the period 1962-1966.
Nicholson (1976, 1978a)	Schefferville, Canada	Vegetation can be removed and snow accumulated by fences to modify ground thermal conditions; heat flux computations are given based on 5.5- and 16.5-m depths.
Ohmura and Muller (1976, 1977)	Axel Heiberg Island, Canada	Heat balance of tundra is given with emphasis on snow melt and active layer developments.
Rouse (1975)	Hudson Bay Lowlands, Canada	Present analyses of mid-summer radiation balance for a shallow tundra lake, wet ridge tundra, natural spruce-lichen woodland, freshly burned woodland, upland lichen heath, and 25-year-old burn.
Rydén (1978)	Abisko, Sweden	Water balance and energy exchange for a tundra mire are presented and results compared with Barrow, Alaska, and several other sites.

Reference	Location	Synopsis
		Microclimate and Energy Balance (cont'd)
Skartveit et al. (1975)	Fennoscandia	Energy flow, microclimatic and climatic components at three arctic and subarctic sites are summarized.
Smith (1975)	Canada	Significant differences in thermal regime exist under various vegetation types; mean annual ground temperature decreases with increasing vegetation.
Weller and Holmgren (1974)	Barrow, Alaska	The microclimate is described and daily heat components computed and summarized by periods throughout the year.
		Modeling Excludes pipeline and other construction-related modeling.
Abbey et al. (1978)	Tuktoyaktuk, Canada	Two index models for predicting ground heat flux during the thawing period are presented and verified; one is based on cumulative heat radiation and the other on cumulative air temperatures.
Arnold (1978)	Non-site-specific	A model is described for estimating ground surface temperatures based on relative humidity and point temperature.
Atwater and Pandolfo (1975)	Barrow, Alaska	The relative magnitude of thermal modification and moisture changes due to towns in tundra are simulated.
Goodrich (1978)	Non-site-specific	Non-linear effects associated with temperature-dependent soil thermal conductivity and soil latent heat can significantly affect the snow-ground temperature interaction.
Goodwin (1976)	*Barrow, Alaska*	Summer soil temperatures on several microrelief elements were obtained and the sensitivity of diurnal near-surface thermal regimes to spatial variability in surface conditions is explored through development and use of models of the surface energy balance.
Goodwin and Outcalt (1974)	Canada	The effect of organic layer removal and drying of the soil surface upon active layer thicknes is simulated; wetness is more sensitive than peat removal in the model.
Goodwin and Outcalt (1975)	Barrow, Alaska	A digital computer model simulates the annual evolution of the thermal regime in the snow cover and active layer.
Guymon and Luthin (1974)	Non-site-specific	A one-dimensional coupled heat and moisture transport is developed.
Lord et al. (1974)	Barrow, Alaska	Interactions of thaw lakes and surrounding tundra are simulated by one- and three-dimensional models.
Lunardini (1978)	Non-site-specific	A theoretical equation for N-factor as a function of air index, seasonal surface heat transfer exclusive of convection, surface coefficient of convection, and soil thermal properties is developed.
McGaw et al. (1978)	Barrow, Alaska	Precise soil temperatures and measured thermal conductivity data for wet organic-rich soils are combined to calculate summer heat fluxes to a depth of 1 m.
McRoberts (1975)	Non-site-specific	Thawing under the natural active layer occurs according to the equation $X = \alpha\sqrt{t}$ (X = depth of thaw, t is time, and α is a constant expressed as $cm/s^{1/2}$).

Reference	Location	Synopsis
		Modeling (cont'd)
Miller (1975)	Non-site-specific	A surface heat balance simulator is described which can be used to predict permafrost temperatures due to disturbance and to permafrost protective schemes.
Ng and Miller (1975)	Barrow, Alaska	Model structure and initial validation of a tundra canopy soil temperature-thaw model are presented.
Ng and Miller (1977)	Barrow, Alaska	Calculated air and soil temperature agree within 1°C of measured profiles and thaw is generally predicted within 1 cm for an improved canopy-soil temperature model.
Outcalt et al. (1975)	Barrow, Alaska	Snow ripening, melt, and accumulation and active layer temperatures are simulated in conjunction with a snow fence modification experiment.
Outcalt and Brown (1977)	Fairbanks, Alaska	The thermal modifications of forest clearing, snow removal and accumulation and pavements are simulated.
Outcalt and Carlson (1975)	Non-site-specific	A simple surface climate simulator is described which can be used to simulate the surface energy budget and soil thermal evolution.
Sheppard, et al. (1978)	Non-site-specific	Verification of coupled flow model using detailed laboratory and field experiments.
Smith (1977)	Eureka, Canada	A model which simulates microclimatic and ground thermal regimes is evaluated using field data for a dry and wet site, and the computer program and user's manual are presented.

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